Capture Zone Evaluation Report

Tronox LLC
Henderson, Nevada

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Responsible CEM for this project

I hereby certify that I am responsible for the services described in this document and for the preparation of this document. The services described in this document have been provided in a manner consistent with the current standards of the profession and, to the best of my knowledge, comply with all applicable federal, state and local statutes, regulations and ordinances.

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1 INTRODUCTION

1.1 Purpose and Overview

Northgate Environmental Management, Inc. (Northgate) has prepared this report on behalf of Tronox LLC, for the Tronox facility located in Henderson, Nevada (Site; Figure 1-1). The purpose of this report is to present the results of a revised capture zone evaluation (CZE) for the groundwater extraction and treatment systems (GWETS) at the Tronox Site. This CZE has been revised from the previous evaluation presented in *Interim Capture Zone Evaluation and Vertical Delineation Report* (Northgate, 2010c) to address January 26, 2010 comments from the Nevada Division of Environmental Protections (NDEP, 2010a). As requested by NDEP in their final comments on the interim CZE report (NDEP, 2010c), Northgate's previous responses to the January 26 comments (Northgate, 2010b) have been updated and are resubmitted as Appendix A to this document.

In response to the January NDEP comments, the evaluation presented in this report follows the six steps defined in the 2008 United States Environmental Protection Agency (USEPA) CZE guidance (USEPA, 2008). Also in response to the comments, Northgate prepared a *CZE Work Plan* (Northgate, 2010d), approved by NDEP May 24, 2010, and a *Hydrogeologic Modeling Work Plan* (Northgate, 2010e), approved by NDEP on July 27, 2010. The work described in these plans has been implemented over the past several months. Northgate used the new data generated from the CZE field work in conjunction with existing data to refine previous evaluations of groundwater flow and perchlorate and hexavalent chromium distributionin the Study Area shown in Figure 1-1. To support the CZE, Northgate constructed a three-dimensional hydrogeologic model (Step 4 in the 2008 USEPA guidance) encompassing all three well fields, and drawing on both Site-specific and the BMI Complex Study Area data. In addition to being a key element of this capture zone evaluation, Northgate anticipates that this model will be an important tool for ongoing optimization of the GWETS and other predictive scenarios.

1.2 Background

Tronox operates three GWETS associated with its facility: (1) the onsite Interceptor Well Field (IWF) and barrier wall, (2) the Athens Road Well Field (AWF), and (3) the Seep Well Field (SWF) (Figure 1-1). Hexavalent chromium in groundwater from the IWF and AWF is reduced to trivalent chromium through a ferrous sulfate treatment system, and perchlorate in groundwater from all three systems is treated using perchlorate-reducing bacteria in a fluidized bed reactor. Following treatment, the groundwater is discharged to the Las Vegas Wash under a National Pollutant Discharge Elimination System (NPDES) permit.

In accordance with the Consent Order for remediation of chromium-impacted groundwater finalized on September 9, 1986, and the Administrative Order on Consent for remediation of perchlorate-impacted groundwater in the Henderson area, Tronox conducts an annual groundwater monitoring event that includes both water level measurements and groundwater sampling for perchlorate, hexavalent chromium, chlorate, nitrate, and total dissolved solids (TDS) analyses, and that is coordinated with several neighboring companies. Groundwater monitoring results and details regarding the remediation systems' operations are provided in annual remediation performance reports (e.g., Northgate, 2010h). Additional monitoring of the groundwater remediation system is conducted quarterly and monthly. These monitoring results indicate significant capture and ongoing reduction of the perchlorate and hexavalent chromium plumes. The ultimate measure of the success of these GWETS is perchlorate loading in the Las Vegas Wash, which has declined by nearly 94% over the last 10 years of groundwater capture system operation (Northgate, 2010h). While this loading includes the Tronox plume, the AMPAC plume to the west, and other sources to the east, this reduction in loading is due almost exclusively to capture of the Tronox plume.

Since the beginning of the GWETS operation, Tronox has periodically evaluated their effectiveness, as reported in groundwater monitoring reports. In commenting on the Tronox *Semi-Annual Remedial Performance Report for Chromium and Perchlorate* dated February 28, 2007, NDEP (NDEP 2007a) requested that Tronox evaluate the effectiveness of its groundwater capture systems by considering at least three of six "lines of evidence" defined by U.S. Environmental Protection Agency (USEPA) guidance available at that time (USEPA 2002, 2005). In response to that request, a draft work plan was provided to NDEP on May 30, 2007 (ENSR 2007a). On June 26, 2007, NDEP provided comments on the *Draft Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems* (NDEP 2007b). Additionally, McGinley also provided a report dated June 30, 2007, describing the results of capture analysis using both an analog approach and a numerical groundwater model constructed for the AWF. In that report, McGinley evaluated well field capture efficiency and provided recommendations to further evaluate the capture zone at Athens Road. Following discussions with NDEP, and in response to their June 2007 comments, and in consideration of the recommendations provided by McGinley (2007), a revised work plan (ENSR 2007b) was prepared and submitted on August 29, 2007. Subsequently, NDEP provided additional comments on October 3, 2007 (NDEP, 2007c). On November 28, 2007, Tronox provided a letter responding to the additional NDEP comments (Tronox, 2007). On December 11, 2007, NDEP approved the revised work plan with a few exceptions noted for the administrative record (NDEP 2007d). Field work consisting of borehole drilling, lithologic sample description, geotechnical sampling, well completion, well development, and well testing was completed by March 2008.

On August 25, 2008, Tronox submitted the Groundwater Capture Evaluation as Appendix B of the *Annual Remedial Performance Report for Chromium and Perchlorate, July 2007-June 2008* (ENSR, 2008). Additional drilling of two soil borings and completion of one recovery well (I-AB) at the west end of the barrier wall was proposed in this report, and was completed in mid-2009.

On October 6, 2008, NDEP provided comments on the Annual Remedial Performance Report and the Groundwater Capture Evaluation, requesting submission of a stand-alone Revised Groundwater Capture Evaluation Report (NDEP, 2008). A monitoring well completion program for eight Middle water-bearing zone (WBZ) wells, for the dual purpose of further delineating the vertical extent of contaminant plumes and vertical hydraulic gradients at the Site, was added to the scope of work in October 2008. These wells were completed in September and October 2009. The information and analyses from these new wells were incorporated into the *Interim Groundwater Capture Evaluation and Vertical Delineation Report* (Northgate, 2010c).

As described in Section 1.1 above, additional CZE field work has been conducted and a hydrogeologic model has been constructed over the past several months in response to remaining NDEP comments on the interim CZE report. As described in the CZE work plan (Northgate, 2010c), the CZE field work included scope to:

1. Update and improve the existing GWETS, including replacement or re-establishment of previous piezometers/monitoring wells and connection of existing but unused recovery wells;
2. Address remaining CZE data gaps identified by Northgate and NDEP; and
3. Collect additional data to enhance the CZE.

Data generated during this CZE field work are included in Appendices B and C. The following paragraphs provide a brief description of each of the three well fields and summary of the CZE field work for each. Table 1-1 lists the operating extraction wells for the IWF, AWF, and SWF and their average pumping rates for the third quarter of 2010.

Interceptor Well Field – A bentonite-slurry barrier wall was constructed as a physical barrier across the higher concentration portion of the perchlorate/chromium plume on the Tronox property. The barrier wall is 1,600 feet long, about 60 feet deep, and is combined with a series of 23 operating groundwater extraction wells that are located immediately upgradient (south) of the barrier wall (Table 1-1). The IWF currently pumps about 72 gallons per minute (gpm) from the Shallow WBZ, dewatering the Qal and the upper portion of the Upper Muddy Creek formation (UMCf) in the vicinity of the pumping wells. Most of the wells comprising the IWF are between

35 to 50 feet deep and completed in both the Qal and unconfined portions of the UMCf. Approximately 250 feet downgradient of the barrier wall, Lake Mead water is injected into the Qal along a 800-foot long trench at a rate of approximately 57 gpm.

In addition to replacing/re-establishing monitoring wells as needed, the CZE investigation fieldwork associated with the IWF included (Figure 1-2): (1) installing eleven piezometers adjacent to extraction wells to provide additional water level measuring points for evaluating capture; (2) installing twelve new UMCf wells singly and in clusters to improve spatial definition of hydraulic conductivity, hydraulic gradient, and contaminant distribution in the UMCf near and upgradient of the wall; and, (3) conducting a barrier wall investigation, including permeability testing of the wall material and pumping/monitoring of four new temporary extraction wells downgradient of the wall (see Appendices B through D for additional information on these investigations). Two new extraction wells (I-AC and I-AD) were also installed to improve capture at the east end of the barrier wall/well field. Connecting these two new wells and five additional recently-installed extraction wells to the IWF recovery system has been delayed due to soil remediation activities in the area, but is expected to be accomplished by the end of 2010. The five additional extraction wells include three new wells within the interior of the well field (I-W, I-X and I-Y) and two wells to improve capture at the west end of the barrier wall/well field (I-AA and I-AB), as described in the Interim CZE report (Northgate, 2010c).

Athens Road Well Field – Located approximately 8,200 feet north (downgradient) of the barrier wall and IWF, the AWF consists a series of 14 groundwater extraction wells at seven paired well locations. The wells span roughly 1,200 feet of the alluvial paleochannels and pump from the Shallow WBZ at a combined rate of about 280 gpm (Table 1-1). The extraction wells are screened across the thickness of the saturated Qal. In addition to replacing/re-establishing monitoring wells as needed, the CZE investigation fieldwork in the AWF included (Figure1-3): (1) installing ten new monitoring wells to provide additional definition of water levels and contaminant distribution in the Qal channels and adjacent UMCf; and, (2) replacing a low-producing extraction well with a deeper well to improve production.

Seep Area Collection System – Located near the Las Vegas Wash approximately 4,500 feet north (downgradient) of the AWF, the system includes a surface pump (sump) for the intermittent surface stream (seep) flow and nine groundwater extraction wells in the SWF to capture subsurface flow. The extraction wells are completed in the Qal and pump from the Shallow WBZ at a combined rate of about 530 gpm. As part of the CZE investigation, Tronox planned to install three new monitoring wells to improve definition of groundwater flow in the SWF, but access was not granted by Basic Management Incorporated (BMI).

1.3 Report Organization

In addition to this Introduction, this report comprises the following sections:

- Section 2 provides an overview of the capture zone evaluation steps, as defined in EPA's guidance for CZE (EPA, 2008).
- Sections 3 through 7 describe the site conceptual model, target capture zone definition, methods for estimating hydraulic capture, and resulting lines of evidence to evaluate the effectiveness of the pump and treat systems in meeting remedial goals. The sections follow Steps 1 through 5, respectively, as defined in the EPA guidance (EPA, 2008).
- Section 8 combines the capture zone results based upon the three-dimensional flow model with additional lines of evidence, and discusses discrepancies and uncertainties in the analyses. Section 8 also summarizes the modeled capture zones in terms of plume mass captured. Recommendations for further evaluations using the numerical model to improve and/or optimize the GWETS system are provided.
- Section 9 lists references cited in the document.
- Appendices to the report include updated response to NDEP comments on the previous CZE report (Northgate, 2010c), data and results from the CZE Workplan (Northgate, 2010d), the groundwater modeling report, perchlorate and chromium data sets used to develop the 3-D plumes, and response to NDEP comments on the *Hyrdogeologic Groundwater Model Inputs* technical memorandum dated October 26, 2010.

2 CAPTURE ZONE EVALUATION STEPS

As described in Section 1.1, Northgate used existing Site data and the new data collected according to the CZE work plan (Northgate, 2010d), as well as data from the regional database maintained by NDEP, and reports prepared by others within the Study Area, to revise the Site capture zone evaluation following the 2008 USEPA guidance. This evaluation of groundwater capture builds on the previous evaluation presented in the revised *Interim Groundwater Capture Evaluation and Vertical Delineation Report* (Northgate, 2010c) and uses multiple lines of evidence to evaluate hydraulic capture at the well fields. Although capture was examined at all three well fields, this evaluation focused on the IWF and AWF.

The following subsections briefly describe the work associated with each of the six steps for capture zone evaluation that are presented in the 2008 USEPA guidance. As described below, the use of the new groundwater flow model is a key element of this evaluation. The methods and results for Steps 1 through 6 are discussed in detail in Sections 3 through 8, respectively.

2.1 Review Site Data, Conceptual Site Model, and Remedy Objectives (Step 1)

Step 1 of the USEPA capture zone evaluation process includes three parts: 1) evaluating the available plume definition and hydrogeologic data to determine if they are adequate for capture evaluation; 2) confirming that there is an adequate Site Conceptual Model (SCM); and, 3) assessing whether the remedy objective is clear. The first part of Step 1 (i.e., assessing data adequacy) has been under evaluation since at least mid-2007, with a number of identified data gaps already filled, as described in the revised *Interim Groundwater Capture Evaluation and Vertical Delineation Report* (Northgate, 2010c). Additional data collection activities recently conducted to enhance the capture zone evaluation were described in *Capture Zone Evaluation Work Plan* (Northgate, 2010d), and these data have been incorporated into the evaluation. As discussed later in Section 3, previously developed SCMs for the Site (e.g., ENSR International, 2005) have been refined in the CZE to address the second part of Step 1. Regarding the third part of Step 1, Tronox's current groundwater remedy objective is to minimize and continue to reduce the perchlorate loading to the Las Vegas Wash. This is being accomplished through plume containment using the three-well-field GWETS described in Section 1.

2.2 Define Site-Specific Target Capture Zone(s) (Step 2)

Target capture zones have not been formally established for the Site well fields. Recent input from NDEP (NDEP, 2010b) is that Tronox needs to "demonstrate 95% capture" at the IWF and AWF, and that Tronox should "compare specific perchlorate concentrations iso-contours to determine the impact on the percent capture by expanding the capture zone by considering smaller perchlorate concentrations”. Tronox’s assessment of these targets is presented in detail in Sections 4 and 6. As agreed to by NDEP (NDEP, 2010d), target capture for the SWF is not addressed in this report.

Site orders require cleanup of both chromium (1986 Consent Order) and perchlorate (2001 Administrative Order on Consent) in groundwater. Perchlorate has been the focus of previous capture zone evaluations and is the focus of this evaluation because it is spatially more extensive and is the only contaminant that presents an imminent threat to human health due to its impact on Lake Mead drinking water source. However, capture of hexavalent chromium is also considered, as discussed in Sections 4 and 6. Site groundwater also contains other contaminants, which originate from both on- and off-Site sources. Capture of these additional chemicals is not evaluated in this report.

2.3 Interpret Water Levels (Step 3)

Water levels measured in existing and new Tronox wells were used for this part of the evaluation. As described in Section 1.2, 24 new piezometers/monitoring wells in the IWF and ten new monitoring wells in the AWF were installed per *Capture Zone Evaluation Work Plan* (Northgate, 2010d) to enhance the water level measuring point network. As described in Section 5, Northgate used Site water level measurements in Step 3 of the CZE for computer-aided interpretations of horizontal capture in the Shallow Water Bearing Zone (WBZ) and evaluation of vertical gradients at closely spaced wells completed within different WBZs. Monitored water levels were interpreted to develop the three dimensional potentiometric surface discussed later in Section 6.

2.4 Perform Calculations (Step 4)

The 3-D groundwater flow model plays the key role in this part of the capture zone evaluation. As described further in Section 6, it was calibrated using the measured Site water levels and contour map, and the water flow budget. In addition to defining capture zones under the current system operation at the IWF, AWF, and SWF, particle tracking was performed using the flow model to:

1) Determine what portion of groundwater flow is and is not being captured at each well field. Interpreted 3D perchlorate envelope was used as the initial condition in transport calculations using the MT3D code (Zhang, 1990).
2) Predict where and when perchlorate originating at various locations and depths within the UMCf will enter the Qal. The purpose of this exercise was to confirm that the perchlorate

will eventually be captured by the Qal recovery wells and to estimate how long it will take for this to happen.

As suggested in the guidance (USEPA, 2008), Northgate also performed simplified analytical calculations for expected capture width and flow rates for comparison with the model.

2.5 Evaluate Concentration and Mass Trends (Step 5)

This step involved expanding and updating the evaluation of perchlorate and hexavalent chromium concentration trends downgradient of the IWF and AWF that was presented in *Interim Groundwater Capture Evaluation and Vertical Delineation Report* (Northgate, 2010c). This evaluation is based on monitoring data collected through May 2010 for remedial performance reports, as well as some more recent data for the newly-installed wells.

2.6 Interpret Capture and Identify Next Steps (Step 6)

The last step described in the USEPA guidance (USEPA, 2008) involves assessing the interpreted capture zones based on Steps 1 through 5 and identifying uncertainties in interpretation, identifying possible data gaps, and determining whether target capture is being achieved. If target capture is not indicated, modifications to achieve target capture are proposed. Uncertainties were evaluated by comparing the results of different lines of evidence for capture and through a sensitivity analysis of the groundwater flow model. Data gaps for assessing capture have been identified and addressed over the past few years and remaining identified gaps for the IWF and AWF have been filled per the approved CZE field work plan (Northgate, 2010d).

The multiple lines of evidence were used to determine what capture is being achieved under current conditions and to confirm that the groundwater flow model can be used to reliably predict the effects of changes to the GWETS. A final step of the capture evaluation uses the groundwater flow model to predict what capture improvement is expected to be achieved after the seven new IWF wells and the deepened AWF well (see Section 1.2) are on-line, additional enhancements to the AWF have been made, and the system has reached steady-state conditions.

3 SITE CONCEPTUAL MODEL

A site conceptual model (SCM) integrates Site information about the setting, the sources of contaminants, the geologic and hydrogeologic conditions, the observed distribution and inferred transport of contaminants, and the potential contaminant exposure routes and receptors. The 'Site' terminology used in this section and illustrated in Figure 1-1 is as follows: the Tronox Property includes the area within the Tronox property boundary; the Site includes the area within the corridor where Tronox has a network of monitoring and extraction wells; and the Study Area includes the area within the domain of the groundwater flow model, which is described further in Section 6. The SCM is used as a basis for establishing the Site remedy, including the specific goals for groundwater capture in the GWETS. A SCM evolves as more information becomes available, and previous information presented in reports (e.g., ENSR, 2005) formed a basis for identifying data gaps and additional evaluation needed to better assess groundwater capture at the IWF and AWF (Northgate, 2010c, d). This SCM is updated by new data collected to better define hydraulic heads, hydraulic properties, and contaminant concentrations in the areas nearby the IWF and AWF. In particular, the SCM focuses on elements pertaining to the Site hydrogeology used as the basis for input to the groundwater flow model presented in Section 6.

3.1 Setting

The Study Area is located in the southeast portion of the Las Vegas Valley near the Las Vegas Wash (Figure1-1). The Study Area includes industrial facilities known as the Black Mountain Industrial Complex (BMI Complex comprised of Tronox, BMI, Chemstar, Pioneer/Olin Chlor-Alkali/Stauffer/Syngenta/Montrose (POSSM), and Titanium Metals Corporation (Timet)), the Henderson wastewater treatment facility, and residential areas (Figure 1-1). The Las Vegas Wash crosses the Study Area along it's northern boundary, and the topography is characterized by a smooth slope from the McCullough Range south of the Study Area northward to the Las Vegas Wash. Ground surface elevations within the Study Area range from approximately 1,875 feet in the south to 1,500 feet (mean sea level) in the north.

3.2 Sources of Contaminants

Industrial activities have occurred on the BMI complex since 1942, which was originally sited and operated for the U.S. government as a wartime magnesium production plant (Kleinfelder, 1993). The BMI magnesium production facility consisted of the following major facilities:

- A brine purification facility that dissolved solar salt and removed calcium, potassium, strontium, sulfate, and bicarbonate impurities via a precipitation and filtering process;

- A chlor-alkali plant to produce sodium hydroxide and chlorine gas from the electrolysis of purified sodium chloride brine;
- A plant that created pellets of magnesium oxide and a carbon source;
- 10 Unit Buildings, each containing chlorinators that created molten magnesium chloride by reacting the magnesium oxide/carbon pellets with chlorine gas at high temperature and banks of electrolytic cells that produced magnesium metal by electrochemical reduction of the molten magnesium chloride;
- An extensive system of surface impoundments that were used to receive process effluent for evaporative disposal. This system originally included the Trade Effluent Ponds, and later included the Upper and Lower BMI Ponds, and the associated Alpha and Beta ditches used to transport effluent to the Ponds; and
- Associated support buildings for the storage and transport of raw materials and the purification and processing of magnesium metal into ingots.

During government operations, extensive volumes of liquid wastes containing dissolved and suspended solids were discharged to four unlined Trade Effluent Ponds. These liquids were generally composed of acid effluent and waste caustic liquor containing high levels of total dissolved solids (TDS), dissolved metals, and to a lesser degree, chlorinated organics (see references in Kleinfelder, 1993). Waste water originating from site processes was also discharged to a storm sewer system that emptied into unlined drainage ditches (e.g., Alpha and Beta Ditches). The unlined drainage ditches routed waste water to a system of unlined ponds currently known as the Upper and Lower BMI ponds. Solid materials were placed in an open area south of the Trade Effluent Settling Ponds and north of the caustic settling ponds (see references in Kleinfelder, 1993). Although originally intended for evaporative disposal, these unlined surface impoundments allowed significant quantities of process effluent to infiltrate into the deep soil and percolated to groundwater.

Following the end of magnesium production in 1944, the BMI complex was subdivided into three primary production areas. The facilities that comprise the present Site include: six process unit buildings (Units 1 through 6) and their attached chlorination buildings, rectifier buildings, motor generator buildings, and bridges; a flux plant; peat storage areas; an area with a salt storage building, pulverizer building, tunnel kiln building, rotary kiln building, pellet storage building, and magnesite silos; various other buildings and open storage areas; and an area occupied by two and one-fifth of the original four Trade Effluent Disposal Ponds.

Process activities at the Site since 1945 include the production of chlorate and perchlorate compounds, boron and boron-related compounds, and refined manganese oxide. From 1945 until the mid-1970s, process effluents were sent to the unlined Upper and Lower BMI Ponds via the Beta Ditch and manganese-related wastes were disposed in onsite leach beds. In the early 1970s, under the federal NPDES program, the industries at the BMI Complex curtailed waste discharges to the Upper and Lower BMI Ponds. Following 1976, process effluents were sent to onsite lined surface impoundments to comply with zero-discharge standards. Several of these lined surface impoundments reported a number of known releases and liner failures and were eventually replaced with more effective double-lined systems.

3.2.1 Constituents of Concern

The primary constituents of concern associated with the groundwater containment and extraction systems have been chromium and perchlorate. Tronox (then Kerr-McGee) began extracting and treating groundwater at the Site for hexavalent chromium at the IWF in accordance with a 1986 Consent Order. Following the discovery of perchlorate in groundwater at the Site during the late 1990s, the AWF and SWF were constructed, and a bentonite-slurry barrier wall was constructed downgradient of the Interceptor wells to improve capture there. While perchlorate and chromium are the constituents driving the groundwater remediation, the compliance monitoring described in the annual reports (e.g., Northgate, 2010a) also includes TDS, nitrate, and chlorate. In addition, the Phase A, Phase B, and other available data show that Shallow WBZ groundwater at the Site and vicinity has also been impacted by a wide variety of other chemicals, including other metals, volatile organic compounds (VOCs), and organochlorine pesticides (OCPs). While capture of these constituents was not explicitly evaluated in this CZE, their distribution and fate-and-transport were considered, and they may be more explicitly addressed in future evaluations.

3.2.1.1 Hexavalent Chromium Source Areas

Hexavalent chromium in the form of sodium dichromate ($Na_2Cr_2O_7$) was used extensively at the Site in the production of sodium chlorate. Sodium dichromate comprised 0.5 weight percent of sodium chlorate and sodium perchlorate process solutions, and was added to reduce cathode corrosion, increase current efficiencies, and to prevent anodic oxygen generation (Kleinfelder, 1993). Multiple source areas exist for the release of hexavalent chromium into Site groundwater including process units, surface impoundments, and on-site areas where chromium-containing process waste was stored or disposed of. These potential source areas, with brief descriptions, are listed in Table 3-1 and shown on Figure 3-2. There were no off-site sources of hexavalent chromium identified; however, it may have been present in wastewater discharged east of the Site.

3.2.1.2 Perchlorate Source Areas

Perchlorate materials were manufactured at the Site from 1945 until approximately 1993 (Kleinfelder, 1993). Because hexavalent chromium was an ingredient of sodium chlorate and perchlorate solutions, these contaminants generally tend to be comingled in Site groundwater. Multiple source areas exist for the release of perchlorate into groundwater beneath the Tronox property. These source areas include process units, surface impoundments, and on-site areas where perchlorate-containing process waste was stored or disposed of. These potential source areas, with brief descriptions, are listed in Table 3-1 and shown on Figure 3-2. No potential offsite sources that could lead to perchlorate contamination of groundwater on the Tronox property have been identified. Perchlorate releases to groundwater at the former Pepcon Plant site, located west of Tronox, however, is a potential offsite source for groundwater contaminants within the Study Area (Figure 1-1).

3.2.2 Off-Site Sources

The Pioneer/Olin Chlor-Alkali/Stauffer/Syngenta/Montrose (POSSM) property to the west of the Site occupies the location of the former BMI Complex chlor-alkali production facility. Post-1945 process activities on the POSSM property include operation of the chlor-alkali facility to produce chlorine gas, hydrochloric acid, and sodium hydroxide. In 1947, additional manufacturing facilities were constructed to produce pesticides and chlorinated organic compounds. Production of agricultural chemicals and organic compounds ceased in 1983, and production facilities were demolished and removed from the POSSM site in 1984. Operation of the chlor-alkali facility is ongoing at the POSSM property. Since 1945, extensive volumes of process effluents and solid wastes were disposed in onsite unlined ponds and buried on the property. These wastes contained high levels of TDS, chlorinated organic compounds, and extensive amounts of phosphoric acid. Prior to 1976, certain process effluents were routed to the Upper and Lower BMI Ponds. These waste streams included large volumes of sulfuric and hydrochloric acid, as well as sulfonated metabolites of DDT (Hargis and Associates, 2010).

The TIMET property to the east of the Site includes four former BMI process units (Units 7 through 10) and refinery buildings. Activities conducted on what is now the TIMET site have included production of magnesium ingot, titanium tetrachloride, titanium sponge, and titanium ingot. From 1951 until 1972, TIMET disposed of its caustic waste, leach liquor, and other process waste streams to the Upper BMI Ponds via the Beta Ditch. From 1972 until 1976, these waste streams were disposed in unlined surface impoundments on TIMET property. From 1976 to 1982, TIMET built 31 lined surface impoundments on top of the southwestern portion of the Upper Ponds where its process waste streams were discharged. Several of the lined ponds reported liner failures and were upgraded to double-lined systems. In 2005, a water conservation facility went online and discharge to the ponds ceased. The TIMET process waste streams contained high levels of TDS and dissolved metal chlorides (LAW Engineering, 1993).

3.3 Hydrogeologic Framework

The hydrogeologic framework of the groundwater system within the Study Area consists of it's geologic units and hydrogeologic units The subsurface conditions have been defined by data collected from the numerous borings and wells that have been installed at the Site (Figure 3-3). Site well construction information (e.g. wells owned and monitored by Tronox), including the lithologic unit and hydrogeologic unit (or water bearing zone) in which the wells are screened, are provided in Table 3-2.

3.3.1 Geologic Units

Figures 3-4, 3-5, and 3-6 present geologic cross sections adopted from the 2010 Annual Report (Northgate, 2010h) and updated with boring information and groundwater quality data collected for the CZE Workplan (Northgate, 2010d). As shown in the cross-section location map provided in Figure 3-1, A-A' is a west-east cross section paralleling the IWF (Figure 3-4), B-B' is a west-east cross section paralleling the AWF (Figure 3-5), and C-C' is a west-east cross section paralleling the SWF (Figure 3-6). Alluvial fan deposits (Qal), originating from the McCullough Range underlie the entire Site to depths ranging from 13 feet to more than 50 feet as evidenced in Tronox borings logged at the Site (Table 3-2). The alluvium consists of a heterogeneous mixture of highly permeable, well-graded sand and gravel with lesser amounts of silt, clay and caliche, without continuous or distinct units.

The alluvium is deposited on top of the Upper Muddy Creek Formation (UMCf), an older sedimentary formation consisting of at least two units of fine-grained sediments of clay and silt (the first and second fine-grained facies [fg1 and fg2], respectively) interbedded with at least two thinner units of coarse-grained sediments of sand, silt, and gravel (the first and second coarse-grained facies [cg1 and cg2], respectively). The fine-grained facies (fg1) underlies the alluvium, except where it pinches out approximately 1,000 feet north of Lake Mead Parkway (Figure 3-1). Beneath the Site, the UMCf occurs to depths of more than 385 feet below ground surface in Tronox Site borings.

A major feature of the alluvial sediments deposited during infrequent floods, is the formation of buried alluvial channels, or paleochannels that were eroded into the surface of the Muddy Creek Formation. These deposits vary in thickness, and are narrow and linear. These generally uniform sand and gravel deposits exhibit higher permeability than the adjacent, well-graded deposits. In general, these paleochannels trend northeastward (ENSR, 2005). The elevation of the top of the Muddy Creek Formation was mapped to assist in locating these paleochannels (Figure 3-7). These contours are based upon the logs from almost 1,200 groundwater wells and soil borings shown on Figure 3-7.

In borings on the Tronox property, the contact between the alluvium and the Upper Muddy Creek Formation is typically marked by the appearance of a well-compacted, moderate brown silt-to-sandy silt or stiff clay-to-sandy clay, whereas near the Las Vegas Wash, the contact is marked by gray-green to yellow-green gypsiferous clays and silts.

3.3.2 Hydrogeologic Units

From north to south, groundwater in the Study Area ranges from 0 to 80 feet below ground surface (bgs) and is first encountered in either the alluvium or in the Upper Muddy Creek Formation. The uppermost, unconfined to partially confined (i.e., leaky) aquifer is referred to as the Shallow WBZ, and it is defined primarily by water level data that show a similar pattern amongst wells completed in this zone. The Shallow WBZ generally occurs above 90 feet bgs. Approximately 86% of the Tronox Site wells are completed in the Shallow WBZ (Qal, UMCf , or xMCf known as transitional Muddy Creek formation; Table 3-2).

Beneath and in hydraulic connection with the Shallow WBZ is the Middle WBZ that extends to approximately 300 feet bgs . Wells completed within this zone are screened within the UMCf (also referred to as the Muddy Creek Formation [MCf]). Approximately 13% of Tronox Site wells are completed in the Middle WBZ (UMCf). There is currently one well completed within the Deep WBZ. The Deep WBZ is defined as the contiguous water-bearing zone that is generally encountered between 300 to 400 feet bgs (NDEP, 2009). The deepest wells within the Study Area are screened within this zone, and in some reference materials it is referred to as the “Shallow Confined Aquifer.” Within the Study Area, all three WBZs are in hydraulic connection with no laterally extensive aquitards inhibiting hydraulic communication.

3.4 Hydrogeologic Properties

The physics of groundwater occurrence, storage, and movement are controlled by hydrogologic properties that include hydraulic conductivity, porosity, and storage coefficients.

3.4.1 Hydraulic Conductivity

Hydraulic conductivity is the proportionality constant relating groundwater flux to the hydraulic gradient. Table 3-3 provides estimates of horizontal hydraulic conductivity from tests conducted throughout the Study Area, including estimates from slug tests conducted under the CZE Work Plan (Northgate, 2010d). Appendix C contains slug test data and analysis for five new wells screened within the UMCf to improve estimates of hydraulic conductivity within the Middle WBZ (Northgate, 2010d). Table 3-3 groups hydraulic conductivities from well and tracer tests by the lithology reported for each well.

Hydraulic conductivity estimates for the Qal deposits have a geometric mean of 22.7 ft/day and range between 0.1 and 846 ft/day. The three orders of magnitude range in hydraulic conductivity of the alluvium reflect the presence of paleochannels with higher conductivity (e.g. above 100 ft/day where they are noted). The tested combined alluvium/Muddy Creek Formation (Qal/UMCf) and transitional Muddy Creek Formation (xMCf or Qal/xMCf/UMCf) have a geometric mean hydraulic conductivity of 1.7 ft/day and range between 0.04 and 102 ft/day. Tests of the UMCf have a geometric mean of 0.08 ft/day and range between 0.001 and 5 ft/day. Three tests of Las Vegas Wash deposits indicate hydraulic conducitivies around 475 ft/day.

Table 3-4 summarizes the results from laboratory tests conducted on soil samples collected from boreholes within the Site area, including samples collected under the CZE Work Plan (Northgate, 2010d). Laboratory tests are used to provide estimates of vertical hydraulic conductivity on soil samples collected typically as cores from a boring. Within the Qal, tested samples have a geometric mean vertical hydraulic conductivity of 0.31 ft/day. Tests of the UCMf samples have a geometric mean of 0.0022 ft/day.

3.4.2 Porosity

Porosity is a measure of the water bearing capacity of the deposits. Total porosity is a measure of the total volume of voids as a percent of the total volume of soil; it is usually expessed as a percentage. Table 3-4 presents laboratory porosity measurements on soil samples from the Qal and UMCf. An average total porosity of 40% is indicated for the Qal and 56% for the UMCf. Because not all voids are interconnected to allow the passage of fluids, the effective porosity is sometimes used to estimate groundwater velocity or travel times. An effective porosity of 10% is estimated for Qal deposits near the SWF (Errol L. Montgomery & Associates, 2001) and an effective porosity of 20% is estimated for the UMCf (UNLV, 2003).

3.4.3 Storage Coefficients

Storage coefficient is the volume of water released from an aquifer per unit surface area, per unit decline in head (a dimensionless ratio). Under fully confined conditions, this is entirely a function of the compressibility of water and the aquifer matrix. The compressibility of water alone is responsible for a storativity of approximately 1×10^{-7} per vertical foot of aquifer. Thus, a

100-ft thick confined aquifer has a storativity of at least 1×10^{-5}. Under semi-confined conditions, the effective storage coefficient is influenced by aquitard leakage and typically ranges between 0.001 and 0.01.

Specific yield is the storage coefficient under water-table conditions. It represents the volume of water that drains from a unit volume of saturated, unconfined aquifer as a result of gravity. Values typically range from 0.01 to 0.25 (i.e., 1 to 25 percent), somewhat less than aquifer porosity.

For a given rate and duration of pumping, a well's depression of the piezometric surface (i.e., drawdown cone) is determined primarily by aquifer transmissivity and storage coefficient. In the case of a confined or leaky aquifer, the cone of depression remains above the top of the aquifer, representing a change in groundwater pressure but not saturated aquifer volume. In the case of an unconfined aquifer, the water table is drawn down, diminishing the volume of saturated aquifer. Other factors being equal, the diameter and depth of a pumping well's drawdown cone are influenced by the relative magnitude of aquifer transmissivity and storage coefficient as follows:

Aquifer Condition	**Storage Coefficient**	**Trans-missivity**	**Drawdown Cone**	
			Diameter	**Depth**
Confined	Small	Low	Large	Deepest
		High		Moderately Shallow
Un-confined	Large	Low	Small	Moderately Deep
		High		Shallowest
Leaky	Moderate	Low	Moderately Small	Deep
		High		Shallow

For a given set of aquifer properties, the diameter and depth of the drawdown cone increases with increasing pumping rate or duration, except that the drawdown cone of a leaky aquifer stabilizes after a relatively short period of time.

Storage coefficients estimated from four different pumpng tests conducted within the Study Area range from 0.004 to 0.11. Measured values for the Qal (0.02 to 0.11) and the transitional UMCf (0.004-0.089) reflect unconfined to leaky aquifer conditions (Table 3-3) Transmisssivity, in the above table, equals the effective horizontal hydraulic conductivity of an aquifer multiplied by it's saturated thickness. Assuming an average saturated thickness at the extraction wells within the shallow WBZ near the IWF of 15 feet, near the AWF of 18 feet, and the SWF of 63 feet, transmissivities range between 340 ft^2/day at the IWF to 1,430 ft^2/day at the SWF. These transmissivities are relatively high, but may be limited by available drawdown, and pumping drawdown cones are expected to be small to moderately small in diameter and shallow in depth when compared to confined aquifer systems.

3.5 Groundwater Occurrence and Movement

The groundwater zones of interest within the Study Area occur within two distinct sedimentary formations, the alluvial sediment fan deposits and the upper porttion of the underlying Muddy Creek Formation. The results of monitoring nearly 1,100 piezometers and wells during the past approximately 30 years indicate the occurrence of groundwater within these formations. The vast majority of the monitoring wells are screened over 0.5 to 30 foot intervals, providing depth-specific data. Approximately 25 Deep (300- 425 ft bgs), 120 Middle (90-300 ft bgs), and 950 Shallow (up to 90 ft deep) wells and piezometers have been installed and monitored within the Study Area (Figure 3-3).

For regulatory purposes, and consistency between the companies within the BMI Complex, the Shallow WBZ is defined to occur within the unconsolidated deposits (e.g. Qal and UMCf) to a depth of 90 ft bgs, the Middle WBZ to occur within unconsolidated deposits (UMCf) to a depth of 300 ft bgs, and the Deep WBZ to occur within unconsolidated UMCf deposits greater than 300 ft bgs (NDEP, 2009).

3.5.1 Aquifer Thickness

The cross-sections presented in the Annual Remedial Performance Report (Northgate, 2010) and data in Table 3-2 indicate the alluvium varies in thickness from approximately 18 feet to 57 feet beneath the Site. The west-east cross-sections show notable variation in elevation along the interface of the Qal and UMCf, on the order of 15 feet at the IWF, up to 25 feet at the AWF, and up to 10 feet at the SWF. This variation is due to paleochannels that are incised into the top of the UMCf and trend northeastward parallel to the direction of groundwater flow. Where the channel deposits are thickest, the paleochannels provide higher conductivity zones for groundwater flow (Figure 3-7).

The saturated Qal thickness generally increases from south to north, averaging 10 feet at the IWF (Figure 3-4), from 0-28 feet near the AWF (Figure 3-5), and 30-45 feet near the SWF (Figure 3-6). The underlying UMCf is in hydraulic connection with the Qal and occurs to depths of over 400 ft bgs within the Study Area (Table 3-2). The combined Qal/UCMf constitute the near surface aquifer (Kaufmann, 1977) in the Study Area. The near surface aquifer is subdivided into the Shallow, Middle, and Deep WBZ as noted above.

3.5.2 Hydraulic Gradients and Flow Direction

Figure 3-8 presents a potentiometric surface map of the third quarter 2010 Shallow WBZ at the Site. The groundwater elevation contours define the general horizontal groundwater flow direction and the hydraulic gradient. Within the Shallow WBZ, groundwater elevations range from 1,800 feet mean sea level (msl) in the south of the Study Area to 1,535 feet msl in the north at the Las Vegas Wash. Groundwater moves from higher to lower elevations in a direction perpendicular to the contours. The map shows groundwater moving in a north to northeast direction across the Site. The gradient, defined by the drop in groundwater hydraulic head (or elevation) divided by the distance over which the drop occurs is approximately 0.0142 ft/ft across the Site. The shallow groundwater generally mimics the topography, and south of the AWF the gradient is steeper (~ 0.0163 ft/ft) compared to north of the AWF (~ 0.0092 ft/ft). The generally uniform flow pattern is influenced by the presence of higher permeability paleochannels, acting as preferential conduits to flow, and inflecting contours in an upgradient direction (Figure 3-7). Other, localized influences on shallow WBZ groundwater flow include groundwater recovery well fields, the AMPAC reinjection system, the City of Henderson Bird Preserve ponds, a constructed Barrier Wall, and recharge trenches noted in Figure 1-1.

The groundwater gradients may also be affected by water density given that the local groundwater is variably saline. Groundwater elevations calculated from field measurements are corrected for density and expressed as equivalent freshwater heads (or elevations) when estimating vertical gradients between closely spaced wells screened over different depth intervals. Groundwater elevations that are used to map the potentiometric surface within the Shallow WBZ are not corrected for density for several reasons: 1) density corrections use the length of the water column to apply the density factor, and for wells screened within the Shallow WBZ the correction does not significantly change the Shallow WBZ elevations, 2) total dissolved solids data is not available to make corrections for all wells, and 3) at a regional scale, the density corrections would not make a difference in flow direction or gradient..

Vertical groundwater movement is generally upward from the deep to middle to shallow WBZs. Table 3-5 lists wells clusters, well construction information, and density corrected water levels used to estimate vertical gradients in select Site wells that are spaced closely and screened within different WBZs. The spatial distribution of wells used to evaluate the vertical groundwater gradients are shown in Figure 3-9. Data in Table 3-5 show upward (negative) gradients from the Middle to Shallow WBZ on the order of 0.017 to 0.26 ft/ft within the Tronox Site. Data from one well in the cluster M-44, M-152, and M-156 show a slight downward gradient (0.028) between well M-44 and M-152, but the deepr Middle WBZ well, M-156, shows an upward gradient of 0.106. Data from one well pair (TR-7 and TR-8) located near the southern Tronox property boundary indicate an upward gradient of 0.18 ft/ft from the Deep to the Middle WBZ. It is expected that downward gradients have existed locally and transiently within the Shallow WBZ where recharge occurs via applied water, such as the Tronox infiltration trenches and the County of Henderson Bird Preserve unlined ponds. Vertical gradients are discussed further in Section 5, including gradients between wells screened at different elevations within a given WBZ (e.g., Shallow and Middle).

3.5.3 Influencing Factors on Flow

3.5.3.1 Geologic Influences

Geologic influences on the occurrence and movement of groundwater include lower permeability boundaries presented by finer grained sedimentary deposits of the UMCf and enhanced permeability features associated with paleo-channels. Hydraulic conductivity measured from wells inferred to be completed in or near paleochannel deposits are from two to five orders of magnitude higher than that measured from wells completed within the UMCf (Table 3-3). The locations of paleochannels have been inferred from multiple lines of evidence including the topography of the Qal-UMCf contact (Figure 3-7), the hydrogeologic interpretation of the potentiometric surface of the Shallow WBZ (Figure 3-8), previous interpretations of the locations of paleo-channels conducted by Tronox and the other Companies of the BMI Complex, and consistency with the observed spatial distribution of perchlorate movement within the Qal sediments (see Section 3.7).

3.5.3.2 Pumping Influences

Groundwater extraction for mostly remedial purposes began in 1986 within the Study Area. Tronox remedial wells are generally less than 60 feet deep and are screened over much of their length within the saturated Qal. Table 1-1 summarizes the record of average third quarter 2010 groundwater extractions at the Tronox well fields. AMPAC and POSSM, two other Company groups within the BMI Complex, also currently operate groundwater extraction systems (Figure 1-1). Pumping records and the well screen intervals for each of the pumping wells were used in developing the numerical groundwater model (Appendix E). A previous inventory for possible residential or agricultural water supply wells did not identify any wells within four miles of the Tronox Site that extract water from the Shallow, Middle, or Deep Zones (ENSR, 2005).

3.5.3.3 Recharge Influences

Groundwater recharge is water that enters the subsurface from above ground and reaches the saturated zone. Sources of recharge within the Study Area include precipitation, applied water (e.g., irrigation and leaks), and various forms of wastewater discharge (infiltration facilities and ponds). Recharge is the net amount from such sources that is not lost to evapotranspiration and site runoff. Factors that influence the spatial and temporal availability of recharge across the Study Area include:

- Seasonal and climatic precipitation patterns and availability
- Influences of topographic elevation and aspect on precipitation
- Man-made and geomorphic controls on runoff and ponding
- Soil, geologic, and ambient moisture controls on infiltration capacity
- Type and extent of vegetative cover, and
- The location, nature, and variability of applied water and wastewater practices

Average annual precipitation measured in Las Vegas from 1971 to 2000 is 4.49 inches (Kleinfelder, 1993). Recharge from precipitation occurs primarily during high intensity, short duration, summer thunderstorms, and stormwater runoff is largely channeled into storm drains (developed areas) and other conveyance structures (industrial areas), resulting in very little recharge. On the Tronox property, stormwater is mostly contained by a berm constructed along the northern (downslope) property boundary and conveyed to an unlined ditch (called the Beta Ditch). The Beta Ditch is currently plugged near the eastern property boundary, and stormflow that enters it can infiltrate. As shown on the aerial photo basemap south of the IWF barrier wall in Figure 1-2, vegetation growing along the Beta Ditch forms a localized area of recharge.

A significant majority of recharge to the Shallow WBZ within the Study Area occurs via applied water (irrigation of residential and golf course areas and leaks from industrial areas), wastewater discharges (the County of Henderson Birding Preserve unlined ponds and Tronox lined ponds), and reinjection of Lake Mead water at the Tronox infiltration trenches, and the AMPAC reinjection system. Estimates of these recharge components are listed in Table 3-6. Figure 3-10 illustrates monthly precipitation, monthly applied water at the Tronox infiltration trenches, and Shallow WBZ hydrographs of wells located near the infiltration trenches. Hydrographs for wells M-84 and M-85, located approximately 50 feet downgradient of the trenches, show a direct correlation with the amount of applied water at the trenches for the period September 2003 to June 2010. Wells M-87 and M-88, located approximately 200 to 400 feet east and slightly downgradient of the trenches, and wells M-101 and M-102, about 600 feet downgradient of the trenches, show a similar but muted correlation. Total monthly precipitation data for the area do not appear to significantly affect groundwater levels, as particularly noted in the period between September 1997 and January 2003. The data indicate that anthropogenic sources of recharge are predominant within the Study Area. Historically, other water disposal facilities, including the Trade Effluent Ponds, BMI northern and southern rapid infiltration basins, the Timet Ponds, and the County of Henderson wastewater treatment plant have been significant sources of recharge to the Shallow WBZ.

3.5.3.4 Estimated Groundwater Velocities

Based upon the hydrogeologic properties of the Qal and UMCf discussed in Section 3.4, relatively high groundwater velocities are expected in the paleo-channel deposits within the Qal compared to significantly lower velocities within the UMCf. An approximate rate of groundwater flow velocities may be expressed as follows:

	Gradient (ft/ft)	Hydraulic Conductivity (ft/day)	Effective Porosity (%)	Velocity (ft/day)
Groundwater flow within Qal across the Study Area	0.0142	23	10	3.3
Groundwater flow within Paleo-Channels across the Study Area	0.0142	150	10	21.3
Groundwater flow within UMCf across the Study Area	0.0142	0.08	20	0.006

Although gradients vary locally, the data illustrate that groundwater flux within the Qal and paleo-channels dominate. Advective transport of contaminants within the underlying UMCf will account for a significantly lower mass flux across a given Study Area transect when compared to mass flux within the overlying Qal.

3.6 Conceptual Water Budget

Recharge to and discharge from the groundwater system drives groundwater flow within the Study Area. As noted in Section 3.5, applied water currently and historically plays a large role in groundwater flow within the Shallow WBZ. Estimates of recharge are noted in Table 3-6. Discharges from the groundwater sytem include extraction from remedial well fields, flow to phreatophytes near the Las Vegas Wash, flow to seeps at the Las Vegas Wash, and flow across hydrogeologic boundaries established for the Study Area. Estimates of groundwater discharge to phreatophytes, or evapotranspiration, is based upon modeled values from the calibrated BMI Upper and Lower Pond Area Model (Northgate, 2010j). Estimates of groundwater pumping used in the numerical model are based upon pumping records available from Tronox, AMPAC, and POSSM. Estimates of groundwater flux into or out of the WBZs is based upon an evaluation of vertical gradient data for areas within the model domain. Flow from the deeper WBZs was vertically upwards throughout most of the Study Area, except for the northeast region where downward vertical gradients were observed (Northgate, 2010j).

3.7 Nature and Extent of Perchlorate and Chromium Contamination

In general, perchlorate and chromium concentrations in groundwater are highest within the Tronox property and decrease with distance downgradient towards the Las Vegas Wash. However, groundwater remediation at the IWF has resulted in a relatively less-contaminated area immediately downgradient of this system. Overall, the higher concentration plumes of both perchlorate and chromium plumes are narrow relative to their length, due to preferential flow and transport within the higher permeability paleochannels. The perchlorate plume has two areas of high concentration (> 1,000 mg/L) upgradient of the IWF, reflecting two general source areas, while the chromium plume is associated only with the more eastern of these source areas.

Figure 3-11 shows the Shallow WBZ contoured perchlorate plume within the Tronox Site based on data collected in May and June 2010, as presented in the 2010 annual performance report (Northgate, 2010h). This dataset shows the highest perchlorate concentration south of the IWF occurred in well I-A-R (2400 mg/L) whereas north of the recharge trenches the highest perchlorate concentration found was 630 mg/L in well M-44 along the northern Tronox property boundary. As described in the 2010 annual performance report (Northgate, 2010h), significant changes in the perchlorate plume have occurred over eight years. In 2002, the highest perchlorate concentration (M-37, adjacent to I-A-R) contained 5,300 mg/L, whereas in 2010 the same well contains only 2,400 mg/L (Figure 3-11). In 2002, a large area downgradient of the barrier wall contained perchlorate in excess of 1,000 mg/L, and concentrations at the downgradient edge of the plume were as high as 160 mg/L where it intersects the Las Vegas Wash. In 2010, the highest concentration measured downgradient of the recharge trenches was 630 mg/L, and the highest concentration measured in the SWF was 13 mg/L.

Figure 3-12 presents the 2010 annual performance report (Northgate, 2010h) isoconcentration map of the Shallow WBZ chromium plume within the Tronox Site area. The main portion of the chromium plume and highest concentrations occur south of the barrier wall and are cut off by the IWF. South of the IWF, the highest total chromium concentration reported for the 2010 annual sampling event was 39 mg/L in well M-50. North of the recharge trenches the highest total chromium concentration found was 2.9 mg/L in well M-87, located south of Warm Springs Road. Concentrations in well M-12A (25 mg/L in May 2002), located on the trailing edge of the main plume, have declined steadily over time and have been below 10 mg/L since the November 2009 monitoring event. Total chromium concentrations downgradient of the barrier wall and recharge trenches also continue to decline, indicating that the groundwater recovery / barrier system is functioning as an effective barrier to migration of the main portion of the chromium plume.

Contaminant concentrations generally attenutate with depth from the Shallow to Middle WBZs and within the Middle WBZ at a given location. On Site, both pechlorate and chromium appear to extend deepest into the Middle WBZ upgradient of the IWF in the original source areas, and both plumes appear to become shallower with distance downgradient towards the Las Vegas Wash. Available data indicate that hexavalent chromium in Site groundwater does not extend into the Middle WBZ at concentrations above its NDEP risk-based groundwater concentration (RBGC) of 0.1 millligram per liter (mg/L), and perchlorate attenuates markedly with increased depth to below 1 mg/L by approximately 150 feet below ground surface within the Middle WBZ in the area upgradient of the IWF and at shallower depths farther downgradient. The vertical extent of perchlorate and chromium in groundwater is described further in Section 4.3.

3.8 Fate and Transport of Chromium and Perchlorate

Chromium exists predominately in two oxidation states: Cr(VI) and Cr(III). Cr(VI) is mobile in groundwater, acutely toxic, and carcinogenic, while Cr(III) is relatively immobile under most groundwater conditions and is characterized with low toxicity. At concentrations present in Site groundwater, Cr(VI) exists primarily as monomeric chromate ($HCrO_4^-$,CrO_4^{2-}) anions. At higher concentrations, such as those that exist in the sodium chlorate process liquor, Cr(VI) exists as dimeric bichromate ($Cr_2O_7^{2-}$) anions. At the slightly alkaline pH conditions encountered at the Site, Cr(III) readily precipitates to an insoluble chromium hydroxide ($Cr(OH)_3$).

Cr(VI) anions are mobile in groundwater, but have been demonstrated to sorb onto surface sites on iron oxyhydroxides (Leckie et al., 1984). The strength of adsorption of Cr(VI) anions is intermediate between those of strongly binding anions, such as phosphate and arsenate, and weakly binding anions like sulfate (Davis et al., 2000). It has been demonstrated that high concentrations of sulfate can reduce chromate adsorption, but this typically occurs under acidic conditions that are not typically observed at the Site (Leckie et al., 1984). Other naturally occurring anions such as bicarbonate and dissolved silica can also compete for adsorption sites and enhance the mobility of Cr(VI) anions in groundwater (van Geen et al., 1994; Zachara et al., 1987).

Cr(VI) remaining in vadose zone soil is not expected to significantly impact groundwater (Northgate, 2010c). Concentrations of Cr(VI) in Site groundwater are expected to decrease over time due to the ongoing extraction and treatment of contaminated groundwater. Natural attenuation via sorption onto mineral surfaces and via reduction into insoluble Cr(III) hydroxides from reactions with organic carbon may also play a role in reduction of Cr(VI) levels over time.

Perchlorate is a large anion with a relatively low diffuse charge. It is highly soluble and sorbs poorly, if at all, to most mineral surfaces. The partition coefficients for perchlorate sorption to geologic media are essentially zero. It does not form aqueous complexes or react with cations to form insoluble phases. Because perchlorate sorbs so poorly to most geologic materials, in the absence of biodegradation, perchlorate plumes do not attenuate and should move at practically the same velocity as groundwater.

Significant levels perchlorate remain in Site vadose zone soil, and has been identified as presenting an ongoing threat through the leaching to groundwater pathway (Northgate, 2010i; *Tronox/NDEP meeting minutes for February 5 and February 12, 2010*). Soil flushing and other remedial options are currently being considered to address this concern (Northgate, 2010h). Provided that this potential leaching concern is adequately addressed, perchlorate concentrations may increase locally, but would be expected to decline eventually in Shallow WBZ due to ongoing groundwater extraction and injection of Lake Mead water.

3.9 Potential Exposure Routes and Receptors

The identification of potentially exposed populations and exposure pathways related to contaminants in groundwater is important and must be incorporated in the CSM. For a complete exposure pathway to exist, each of the following elements must be present (USEPA, 1989):

- A source and mechanism for chemical release (discussed in Section 3.2 above);
- An environmental transport medium (e.g., air, soil, water);
- A point of potential human or ecological contact with the medium; and
- A route of exposure (e.g., inhalation, ingestion, dermal contact).

Potential contaminant migration pathways at or near the Site exist through air, soil, surface water, and groundwater. Contaminant transport can occur through the air pathway when contaminated soils are present at or near the surface and particulates are mobilized and carried by winds. Contaminants capable of volatizing or releasing gases can move via air through soil as soil gas. Contaminants in surface water and groundwater can also volatize. Contaminants can be transported on- or offsite through surface water movement when flowing across the Site due to rain or other runoff, or in bermed water control features such as in the Beta Ditch. In addition, soluble contaminants can be dissolved and transported across the surface and/or infiltrate into the subsurface, contaminating the vadose zone and possibly continuing into the groundwater. Where contaminated groundwater surfaces, surface water, such as the Las Vegas Wash, may be impacted (ENSR, 2005). Humans may also be exposed to contaminated groundwater through water supply wells.

As discussed above, the Site is currently an active industrial facility. In the future, the Site is expected to continue to be used for industrial and/or commercial purposes. Additionally, consistent with the HRA Work Plan (Northgate 2010a), because the area will remain as part of an active commercial/industrial facility in the future, ecological habitat is not currently sufficient to warrant an ecological risk assessment, nor is it expected to be in the future. Accordingly, the current and future on-site receptors include long-term indoor workers, long-term outdoor workers and short-term construction workers.

3.9.1 Previous Site Risk Assessments

Previous health risk assessments (HRAs) for the Site including RZ-A and the Parcels (e.g., Northgate, 2010g) have focused on near-surface (ten feet below ground surface or less) contaminated soil for future onsite indoor and outdoor commercial workers and future construction workers via direct contact with soil (e.g., incidental ingestion, dermal contact and inhalation of dust). Removing soil that potentially presents an unacceptable risk for these pathways has been the focus of remediation activities at the Site during 2010. Residual contaminants in the soil can be leached through the pore space and into groundwater via water infiltration, and this is also under evaluation for the Site (Northgate, 2010k). Additionally, a Site-Wide Soil Gas HRA has been prepared to evaluate the potential for adverse health impacts that may occur as a result of exposure to chemicals in soil gas via inhalation of indoor or outdoor air (Northgate 2010k). While these VOCs (primarily chloroform) may originate in groundwater, that potential exposure pathway is not the focus of the CZE, but may be considered in future evaluations.

3.9.2 Potential Groundwater Exposure Pathways

In addition to exposure to VOCs volatilizing from groundwater, potential exposure pathways for contaminants in Site groundwater involve its potential use as water supply. The Site groundwater is not a current drinking water source, nor is it likely to be in the future due to its naturally poor quality (see Section 3.2). As discussed in the approved HRA Workplan, ingestion, dermal contact and domestic use (e.g. showering) with groundwater are not considered complete pathways due to the fact that the groundwater is not used as water supply. There are no water supply wells reported within four miles of the Site that extract water from the Shallow, Middle, or Deep Zones (ENSR, 2005). However, shallow Site groundwater does migrate to and discharge into the Las Vegas Wash and then flows into Lake Mead, which is a drinking water source. In addition, groundwater extracted from the Site and treated for hexavalent chromium and perchlorate is discharged to the Las Vegas Wash under a NPDES permit. The migration of perchlorate into the Las Vegas Wash is the primary exposure pathway of concern for Site groundwater, and is the focus of this CZE.

4 TARGET CAPTURE ZONE DEVELOPMENT

4.1 Groundwater Extraction System Goals

A target capture zone is the three-dimensional zone of groundwater that must be captured by the site extraction wells for the GWETS system to be considered successful (USEPA, 2008). Although target capture zones for the Tronox well fields have been discussed amongst representatives of Tronox and NDEP, to date none have been firmly established. Based on recent input from NDEP including discussions between Tronox and NDEP at an April 16, 2010, project meeting, Tronox considered the following in developing the target capture zones proposed herein:

- An overall goal is to minimize to the extent feasible the mass of perchlorate migrating to the Las Vegas Wash and thereby into Lake Mead.
- Specifically at IWF and AWF, a 95 percent perchlorate mass flux capture is the initial goal.
- The incremental percentage of additional mass that could be captured by targeting a series of decreasing isoconcentration contours should be considered at IWF.
- A goal for SWF will be established in the future based upon IWF and AWF capture estimates and possible alternative remedial approaches (e.g., *in-situ* reductive bioremediation) being considered for this area of the plume.

Based on these considerations and other NDEP input (NDEP, 2010b), Tronox developed a three dimensional depiction of perchlorate and chromium concentrations (or three dimensional plume) from recent groundwater quality data. As described below, these three dimensional plumes were used to calculate the percentage of perchlorate plume mass contained with various isoconcentration contours, and these percentages were considered in defining an appropriate plume boundary targeted for capture. As described in Section 6, the three dimensional plume depictions and selected plume boundaries were used to evaluate the percent contaminant mass currently captured by the extraction systems. The chemical data sets, modeling method, and the resulting three dimensional plume figures are discussed below.

4.2 3-Dimensional Plume Definition Dataset and Modeling Method

The concentration and well location data used in the generation of the perchlorate and chromium 3D groundwater plume models were constructed in the following manner. Concentration data for perchlorate, chromium, and hexavalent chromium in groundwater were queried from the BMI Complex, Common Areas, and Vicinity Database (BMIdbase) on November 4, 2010 and copied into a spreadsheet. As the BMIdbase only includes data up to 2009-Q4, the spreadsheet was augmented with more recent data obtained from 2010 groundwater monitoring reports.

At this point, well name conflicts were resolved using well locations as a QA/QC check and merged. The most recent data for each well was selected for inclusion into the concentration datasets. In the case of chromium, both total chromium and hexavalent chromium data were combined. Concentrations were analyzed to determine if the most recent sampling data fell within the range of historical values for that well location. In a few cases where the most recent data did not appear representative, that data was disqualified and earlier data was selected. Only data sampled after January 1, 2008 was considered eligible for inclusion.

Samples with elevated sample quantitation limits (SQLs) were also eliminated from inclusion into the dataset. These high SQLs typically resulted from high dilution levels and led to unreasonably large non-detect (ND) values. For perchlorate, an elevated SQL was defined as greater than one half the mean of the detected values. For chromium, an elevated SQL was defined as greater than 50 ppb.

Average well screen depths and surface elevations for each well were obtained from the "All Wells Database" dated December 22, 2009 and added to the spreadsheet. Wells without screen depth or elevation data were removed from consideration. The final step in developing the perchlorate and chromium datasets was to manually remove wells and to add control points to the west and east of the Site to honor the conceptual model for the Site and AMPAC perchlorate plumes. Further description and the perchlorate and chromium datasets used for the three-dimensional plume modeling are presented in Appendix F.

The three-dimensional perchlorate and chromium groundwater plumes were generated using Environmental Visualization Systems (EVS) by CTECH Development Corporation. Groundwater concentration data was combined with the wells' horizontal locations, surface elevations, and the center of the groundwater screen. EVS uses kriging to interpolate the concentration data in three dimensions. Kriging is a mathematical process that is commonly used the for interpolation of measured data. The concentration data is initially log processed before the interpolation is performed, changing all concentrations into the log of the concentration. EVS provides an expert system to drive the Kriging modules, making it unnecessary for the user to determine the optimal semivariogram parameters, but the settings were customized so the interpolation reflected the ground conditions more accurately. The following parameters were changed for the interpolation:

- The number of nodes in the horizontal direction for the model were increased from 41 to 75, making the model grid finer and the plume smoother.
- The anisotropy was increased from 10 to 25. The higher the number, the less influence the vertical direction has on the interpolation.

The model was limited to a 400 foot thickness, using the groundwater table elevation provided by the groundwater model for the top, and an elevation that was 400 feet below groundwater for the bottom. Without limiting the vertical boundaries, EVS would interpolate the model as a cube and not take into account the elevation variations over the plume area. EVS was then used to generate cross-sections at various locations, as well as calculate the volume and mass of the groundwater plume.

4.3 3-Dimensional Plume Maps

Figures 4-1and 4-2 depict the perchlorate groundwater plume in plan, cross-sectional and oblique views. Although 0.018 mg/L is NDEP's RBGC for perchlorate, 1 mg/L was selected for the lowest contour because below this level there is inherent variability with low concentration measurements and, as shown on Table 4-1, below 1 mg/L the mass of perchlorate represents less than 1% of the total mass. As Figure 4-1 illustrates, even at this concentration there are off-Site perchlorate sources contributing to the Tronox plume downgradient of the IWF. These include one or more apparent sources to the east, which may be related to past wastewater discharge to the former BMI ditches and ponds by Tronox and possibly others. Not shown on Figures 4-1 and 4-2 is the AMPAC perchlorate plume located west of the Tronox perchlorate plume. This plume may also commingle with the Tronox plume at low concentrations near the Las Vegas Wash.

As shown on Figures 4-1 and 4-2, the area of highest groundwater perchlorate concentration (1,000 to 2,400 mg/L) is limited upgradient of the IWF. Moderately high (between 100 and 500 mg/L) concentrations extend as far downgradient as several hundred feet north of the AWF. Lower concentrations (25 mg/L and less) are more broadly distributed and reflect apparent off-Site sources. As indicated in the plume-axis cross section on Figure 4-2, perchlorate concentrations above 1 mg/L do not appear to extend deeper than approximately 150 ft bgs. With the installation of a number of new UMCf wells upgradient and in the immediate vicinity of the IWF (see Appendix B), the depth distribution of perchlorate is now well-constrained in this area. The vertical perchlorate distribution is less well defined between the IWF area and the AWF. For this area, the anisotropy used in the plume model (see Section 4.2 above) has a considerable effect on how the vertical concentration distribution is depicted. Based on the perchlorate concentrations in deeper wells located downgradient of the IWF, the vertical extent of perchlorate between these wells and the AWF may be overestimated.

To provide a frame of reference for the mass flux capture evaluation discussed in Section 6 and as requested by NDEP (NDEP, 2010c), the EVS software was also used to calculate the groundwater perchlorate plume mass within various contours and portions of the plume, and the results of these calculations are presented in Table 4-1. These calculations are based on an assumed average total porosity of 0.5 for both the Qal and UMCf. Due to actual porosity variability and uncertainties in the actual concentration distribution, particularly in the vertical direction as described above, these perchlorate mass calculations are considered rough estimates for providing information on relative mass in different portions of the plume. As shown on Table 4-1, these calculations indicate that approximately 40% of the total plume mass is located upgradient of the IWF. As shown on Table 4-1, 94% of this plume mass upgradient of the IWF is contained within the 25 mg/L contour, an additional 3% falls between the 10 and 25 mg/L contours, 1% falls between the 5 and 10 mg/L contours, 1% falls between the 1 and 5 mg/L contours, and the remaining 1% falls below the 1 mg/L contour.

Figures 4-3 and 4-4 depict the chromium plume using the same views as those used for the perchlorate plume. The 0.1 mg/L RBGC was used as the lowest contour for the chromium plume. As shown on these figures, the chromium groundwater plume extent above 0.1 mg/L is similar to that for perchlorate above 1 mg/L, except that it is not as extensive laterally and vertically and does not indicate as much input from apparent sources east of the Tronox Site as the perchlorate plumes does. Also similar to the perchlorate distribution, the highest chromium concentrations (10 to 39 mg/L) are constrained to the area upgradient of the IWF (Figure 4-3). Groundwater containing moderate chromium levels (0.1 to 1 mg/L) extends downgradient of the IWF, and appears as far downgradient as the AWF in the eastern portion of the plume (i.e., within the more eastern of the two alluvial channels intercepted by this well field).

5 WATER LEVEL INTERPRETATION

The extent of horizontal or vertical capture can be estimated based upon water level contour maps, depicting groundwater flow on a two dimensional plane. Horizontal capture at the well fields can be estimated from a potentiometric map of water levels measured in the Shallow WBZ. Vertical capture can be estimated from a map showing the difference in heads (or water levels) between wells completed in different hydrostratigraphic units (e.g. Shallow, Middle, and Deep WBZs). For the Tronox Site, groundwater flow patterns have been analyzed in three dimensions, using a numerical groundwater flow model, that accounts for anisotropy and three dimensional head distributions. The model is discussed in Section 6.

This section presents a horizontal capture analysis of the Shallow WBZ by interpreting flow lines perpendicular to the water level contours as bounding the flow lines that would reach the IWF and AWF. Capture indicated through an idealized groundwater flow net interpretation is compared to that indicated by the numerical model in Section 8. Vertical gradients between the Shallow and Middle WBZs have also been calculated for specific well clusters at the Tronox Site (see Section 3) and indicate generally upward gradients from the Middle to the Shallow WBZ. The total number and spacing of wells screened within the Middle WBZ (Table 3-2) are not sufficient to create a potentiometric surface map for this unit, and thus a map showing the difference in heads between the Shallow and Middle WBZs could not be constructed. The following subsections describe the data and methods used to interpret water levels and the analysis of horizontal and vertical capture for the IWF and the AWF.

5.1 Data Selection

Water levels measured in existing wells and new wells installed as part of the *Capture Zone Evaluation Work Plan* (Northgate, 2010d) were used to analyze ground water flow patterns and inferred horizontal capture within the Shallow WBZ at the IWF and AWF. Approximately 240 existing wells are monitored routinely to assess groundwater elevations and contaminant concentrations. Wells are monitored monthly, quarterly, or annually to assess seasonal fluctuations and gradient trends. Forty-one new wells installed per the CZE Work Plan provide additional water level data in the vicinity of the IWF and AWF including:

- IWF: 11 piezometers adjacent to select recovery wells to provide accurate measure of drawdown in these areas; 12 new wells screened at varying depths in UMCf to provide additional information on vertical head differences, evaluate potential flow under the barrier wall,; and monitor the lateral and vertical influence of the recovery wells; and four new monitoring wells to restore missing/damaged water level measuring points.

- AWF: eight new monitoring wells in and around the recovery well field; two new monitoring wells screened in the "UMCf high;" one new recovery well, and four new monitoring wells to restore missing/damaged water level measuring points.

Table B-1 in Appendix B lists construction information for each of the new wells, replacement wells, and repaired wells, along with the primary rationale and/or data objective for each well within the CZE Work Plan. Hydrographs for select Site monitoring wells in the vicinity of the IWF and AWF are presented in Figure 5-1. Groundwater levels generally fluctuate in tandem and there are no significant differences (i.e., differences are less than 10 feet) in groundwater levels measured over the past 8 years. Groundwater elevations measured in the third quarter of 2010 were used for this analysis. If third quarter data were not available, data from second quarter 2010 were used. Groundwater levels measured at well PC-98R were excluded from the data set because they appeared anomalous compared to neighboring wells. Water level data collected in 2010 and the values used to prepare the water level contour maps are noted in Table 5-1. Well construction and water chemistry data used for calculating vertical gradients are provided in Table 5-2.

5.2 Methodology

5.2.1 Potentiometric Surface and Horizontal Gradients

Potentiometric surface maps for the Shallow WBZ at the IWF and AWF are presented as Figures 5-2 and 5-3, respectively. A Shallow WBZ potentiometric map for the Tronox Site is presented in Figure 3-8. Potentiometric maps were prepared using KT3D_H2O geostatistical software. The capture zones were estimated using a graphic flow-net analysis based on measured groundwater elevations.

KT3D_H2O is a software program developed by S.S. Papadopulos and Associates that combines several geostatistical programs that allow the user to generate gridded maps of water level elevations while taking into account elements such as point sinks or sources (e.g., extraction or injection wells) and horizontal line sinks or sources (i.e., interception trenches or infiltration galleries; Karanovic et al., 2009). Three Site factors affecting local groundwater flow are: (1) pumping from extraction wells, (2) injection at recharge trenches in the IWF area, and (3) the groundwater barrier wall in the IWF area. The water levels were interpolated in KT3D_H2O using pumping and injection rates from individual extraction wells and the recharge trenches as point sinks and sources (Table 1-1). The injection rate and location was approximated by dividing the combined recharge trench injection rate into four equal fractions and uniformly distributing four sources along the lateral length of the trench.

Groundwater elevation contours were generated in KT3D_H2O using ordinary kriging with an isotropic spherical variogram. Kriging is a geostatistical technique that interpolates the value of a random field (e.g., the groundwater elevation) at unobserved locations using measurements from nearby locations. KT3D_H2O is limited in its ability to account for low or no flow conditions, such as the groundwater barrier wall. Hence the resulting potentiometric surface generated out of KT3D_H2O was further interpolated in ArcGIS using Spatial Analyst, adjusting contour lines as appropriate at the IWF barrier wall and locations where features, such as the “UMCf high” at the AWF affect groundwater flow.

5.2.2 Vertical Gradients

Head differences and vertical gradients were calculated for well pairs screened in the Qal and at various depths in the UMCf. Head differences are simply the difference in the measured groundwater elevation between nearby wells screened in different hydrostratigraphic units. Vertical gradients are the difference in the measured groundwater elevation between wells divided by the vertical distance between the two monitoring points. In both of these calculations, groundwater elevation measurements were first corrected for density differences to account for the variably high TDS content in Site groundwater (Post et al., 2007). For the vertical gradient calculation, the elevation of the midpoint of the well screen was used to calculate the difference in vertical distance. Data used for the vertical gradient analysis are shown in Table 5-2, and well pair locations are displayed on Figure 3-9.

5.3 Analysis

The contoured groundwater elevation data (Figure 3-8) indicate that Shallow WBZ groundwater flows north or northeast beneath the Site, with minor perturbations near the recovery well fields. This map is consistent with a previous map prepared for the Annual Remedial Performance Report (e.g., Northgate; 2010g). Vertical gradients are generally upward, as shown by a comparison of water level data from Deep to Middle, Middle to Shallow, and deeper to shallower Shallow zone wells. Groundwater gradients are locally altered in the vicinity of the IWF (including the barrier wall and reinjection trenches) and AWF. Further interpretation of water level data in the area of the two well fields is provided below.

5.3.1 Interceptor Well Field

Figure 5-2 is a water level elevation map of the Shallow WBZ in the vicinity of the IWF. The groundwater level contours were interpolated using a graphic flow net analysis and adjusted by hand to account for influences affecting flow. The estimated zone of capture is noted as the flow line (perpendicular to groundwater contours) that encompasses the area where horizontal flow within the upper 60 feet is captured by extraction wells located south of the barrier wall.

Well pairs used to estimate vertical gradients in the vicinity of the IWF are shown on Figure 3-9, and presented in Table 5-3. Vertical gradients are generally upward in most well pairs. There is a local downward gradient near well pair M-159/M-160, west of the IWF barrier wall, although both of these wells are completed within the Shallow WBZ. The vertical gradient is downward within two wells screened within the Middle WBZ (well pair M-187/M-188) located upgradient of the barrier wall, northeast of the Chemstar facility. One well pair (TR-7/TR-8) near the southwest property boundary indicate an upward vertical gradient from the Deep to the Middle WBZ.

5.3.2 Athens Road Well Field

Figure 5-3 is a water level elevation map of the Shallow WBZ in the vicinity of the AWF. The groundwater level contours were interpolated and zones of capture estimated as described above in Section 5.3.1. Two new wells (PC-149 and PC-148) were installed within the UMCf high to define groundwater levels in the area between the eastern and western extraction well fields. Groundwater elevation contours show a deflection at the UMCf high, suggesting lower permeability deposits within this area. Currently there are no pumping wells in this area, so capture is not indicated in the area between the AWF sets of extraction wells. Although flow is not captured in this area, it is expected that the mass flux of contaminants would be less than in the adjacent areas where alluvial channels are indicated on cross section (Figure 3-5). Downgradient from the pumping wells the gradient appears to flatten more on the west than the east, due to higher pumping volumes from the western set of recovery wells (Table 1-1).

Well pairs used to estimate vertical gradient in the vicinity of the AWF are shown on Figure 3-9, and presented in Table 5-3. These two well pairs are located just north and west of the western AWF. A measured vertical gradient is upward within two wells screened within the Shallow WBZ (well pair PC-134A/PC-135A). Within 400 feet west of this well pair, there is a very slight (0.006 foot/foot) downward gradient within two wells screened within the Shallow WBZ (well pair PC-141/PC-142). As noted in Section 3.5, vertical gradients within a WBZ could be variable, depending upon the lithology and on how the monitoring wells areconstructed.

6 GROUNDWATER FLOW MODEL AND RELATED CALCULATIONS

Calculations are used to provide additional lines of evidence regarding the extent of capture (EPA, 2008). Simple horizontal analyses related to capture, such as estimated flow rate calculations and capture zone width calculations, can be made quickly and compared to actual well field pumping rates and the estimated contaminant plume width. The simplicity of these analyses require assignation of single values of aquifer thickness, hydraulic conductivity, and hydraulic gradient. As the SCM in Section 3 demonstrates, there are significant variations in these parameters at the Site and at each well field. Therefore a groundwater model was developed to account for these variations both in space and time. This section first presents simple analytical calculations and then summarizes the numerical groundwater flow model used to quantitatively estimate capture of the three-dimensional plume and capture efficiency at each of the well fields.

6.1 Estimated Flow Rate and Capture Zone Width Calculations

Flow rate calculations estimate the pumping rate required to capture the groundwater flux through the estimated extent of the plume (or capture zone). This simple horizontal capture analysis includes assumptions of a homogenous, isotropic, confined aquifer of uniform thickness and fully penetrating extraction wells. None of these assumptions can be strictly applied for this site, however this analysis is included as part of EPA recommendations (EPA, 2008). The flow rate (Q) is expressed as:

$$Q = K * (b * w) * i * \text{factor}$$

Where:
K = hydraulic conductivity (ft/day)
b = saturated thickness (ft)
w = plume width (ft)
i = regional gradient (ft/ft- unitless)
factor = “rule of thumb” is 1.5 to 2.0, intended to account for other contributions to the pumping well such as flux from an injection system or induced vertical flow from another unit, such as the UMCf

The selection of input values are included in Table 6-1. The calculated flow rates are compared to the combined extraction rates at each well field. As shown by the calculated values, the combined average pumping rate of the IWF (73 gpm) exceeds the calculated flow rate for the entire 3.420-foot width of the 1 mg/L perchlorate plume under both the medium (7.9 gpm) and high (30 gpm) hydraulic conductivity scenarios. Similarly, the combined average pumping rate of the AWF (approximately 281 gpm) exceeds the calculated flow rate for the entire 1,300-foot width of the “local” perchlorate plume (see Section 6.2.8 for definition) under the medium hydraulic conductivity scenario (170 gpm). Under the AWF high hydraulic conductivity scenario, (which assumes flow occurs entirely within paleochannels), the calculated flow rate (972 gpm) exceeds the the combined average third quarter pumping rate of 281 gpm. Using these simplifying assumptions, pumping rates at the AWF may not be sufficient to capture the width of the perchlorate plume under assumptions of a high hydraulic conductivity scenario.

The capture zone stagnation point and width calculation is an estimate of the geometry of the zone of capture around a single pumping well. These calculations assume a single pumping well pumps the toal volume of flow (Q) at the center of the well field. The stagnation point is measured in the downgradient direction from the pumping well parallel to the plume axis in the direction of groundwater flow. Y_{well} (the width of the capture zone from a pumping well located at the center of the plume) and Y_{max} (the maximum width of the capture zone) are measured symmetrically from the pumping well perpendicular to the plume axis. The capture zone widths for the IWF and AWF were estimated by assigning the respective total pumping rate at one centrally-located “equivalent well” per well field. For the IWF, the estimated stagnation point is 2,604 feet downgradient of hypothetical “equivalent well”and Y_{well} is a minimum of 4,090 feet (estimated in the high hydraulic conductivity scenario). However, pumping the total flow volume from a single well is not possible as transmissivity is limited by the saturated thickness. For the AWF, the estimated stagnation point is 119 feet downgradient of hypothetical “equivalent well” and Y_{well} is a minimum of 1,271 feet (estimated in the high hydraulic conductivity scenario). Calculated capture zone widths are similar to or larger than the capture zones estimated from the potentiometric surface maps for both the IWF and AWF. Modeled interpretations of groundwater capture in a 3-dimensional field provide more accurate lines of evidence for capture, as discussed in the remaining subsections.

6.2 Capture Zone Analysis Using Flow Model

Tronox developed a three dimensional flow model, the Tronox model, to assist in this quantitative capture zone evaluation and for ongoing optimization and evaluation of Site remediation. The model development in its entirety is described in Appendix E. A summary of the model development and results of the capture evaluation using the model are described below.

6.2.1 Model Domain

A three dimensional, numerical groundwater flow model was developed using the USGS MODFLOW code (McDonald and Harbaugh 1988; Harbaugh et al. 2000) for an area covering the entire the Tronox Site and including its immediately neighboring industrial facilities. The pre- and post-processing was carried out using the Groundwater Vista® software package. The model domain is shown in Figure 6-1. The active area of the model domain is wedge-shaped, narrowing from south to north toward the Las Vegas Wash. From south to north, the proposed model domain extends from south of Lake Mead Parkway to the Las Vegas Wash, approximately 20,000 feet (about 4 miles) in total length. Laterally (perpendicular to the regional groundwater flow direction), the model extends east and west of the Tronox Site to include the existing groundwater treatment systems of AMPAC and POSSM to the west and the proposed groundwater barrier wall and capture wells at the TIMET site to the east. The large extent of the model domain assures reflection of the hydraulic features which may impact the evaluation of groundwater capture zones and future plume evolution, and avoids having the lateral boundaries of the active domain intersect active sources and sinks.

6.2.2 Model Discretization

Horizontal cell size of the model grid varies from 50 ft to 243.75 ft. For the most part, the model grid blocks are uniform and are 200 ft by 200 ft. Near the well fields, the grid is refined by reducing grid size down to 50 ft. Vertically, the model extends downward from the ground surface, through the shallow Quaternary alluvium (Qal) and several hundred feet into the Upper Muddy Creek formation (UMCf). Within the model domain the saturated Qal unit varies in thickness from nearly 0 ft in the south to about 50 ft in the north. The UMCf is a massive unit extending more than 1,000 ft deep. The modeled UMCf terminates at a depth of about 300 ft below ground surface. The Qal and UMCf units were each represented by two and four model layers, respectively. The layer thicknesses were chosen such that most of the extraction wells are screened in Layers 2 and/or Layer 3. Large portions of the top alluvium layer are dry in the southern portion of the model domain.

6.2.3 Model Boundary Conditions

The eastern and the western boundaries were chosen to be roughly coincident with streamlines interpreted from regional groundwater elevation data. These two lateral boundaries were assigned "no-flow" condition. A series of wells were placed in the southern boundary to inject a volume of water known to enter the model domain from the south. The northern boundary terminating into the Las Vegas Wash was assigned constant head values based on river stage measurements. Years of water level measurements in the UMCf indicate that a significant input to the modeled domain comes from upward artesian flow from deeper portions of the UMCf unit. The bottom boundary was simulated as MODFLOW's general head boundary condition (GHB) to simulate that upward flow through the model bottom.

6.2.4 Hydraulic Parameters and Model Calibration

A significant body of information is available for hydraulic conductivity of the Qal alluvium from pump tests and slug tests (Table 3-3). Relatively lesser but adequate information is also available for the UMCf unit. Hydraulic conductivity information was reviewed and screened for inclusion. Where descrepancies existed with well construction or well completion lithology recorded in the All_Wells database or where multiple tests indicated outlier values, data were not used for statistical estimates. Based on these information, horizontal hydraulic conductivities for the Qal alluvium have an arithmetic mean of 35 ft/day and a harmonic mean of 4 ft/day. For the UMCf available information indicates an arithmetic mean hydraulic conductivity of about 2 ft/day and a harmonic mean of about 0.013 ft/day. The harmonic and arithmetic means were used to set the lower and upper bounds during the calibration stage. Final values of all the parameters were chosen based on an exhaustive calibration using head data from 263 measured water level elevations over a nearly steady period from 8/2008 to 3/2009. The comparison of simulated head values at these 263 locations to measured values indicates an adequate agreement given the rather large range of measured values of about 285.8 ft (Figure 6-1). The calibration indicated that the model predicted heads have a residual mean of 1.26 ft with a Root Mean Squared (RMS) error of about 6.2 ft. The agreement is relatively better in the Qal alluvium than that in the UMCf Muddy Creek. Further details of the model, parameter values and calibration results are provided in Appendix E .

6.2.5 Use of Plume Model in Capture Zone Evaluation

As described in Section 1, three remedial extraction systems are in operation at the Tronox site – the IWF, AWF and the SWF. The primary objective of the development of the Tronox model was to evaluate how efficiently the IWF and AWF extraction systems are capturing the monitored perchlorate plume. As described in Section 4, a three dimensional perchlorate plume envelope was developed based on the available data (see Figures 4-1 and 4-2). For the purpose of capture zone evaluation using the Tronox model, the 1 mg/L perchlorate plume contour was estimated at the mid-height of each of the six model layers. As described in the next subsection, the resultant plume contours were used to define starting points for the endpoint analysis.

6.2.6 Capture Zone Evaluation by Endpoint Analyses

The calibrated Tronox model was used to carry out endpoint analyses for particles released at the mid-height of each model layer. The endpoint analyses were performed using the MODPATH code (Pollock, 1994) which is a particle tracking companion code to MODFLOW. On the basis of head values from a MODFLOW analyses, the MODPATH code can track the movement of particles along streamlines. In particular, the endpoint analyses can determine which of the released particles are discharged at a boundary of interest marked by a reach number. In the present case the endpoint analyses determined which of the particles released at each layer were discharged (i.e. captured) at the extraction wells. The Tronox model was used to perform the endpoint analyses. At each layer, particles were released at a uniform density of one particle every 50 ft in X and Y directions. Figures 6-2 through 6-6 display the results of the endpoint analyses. Dots indicate the locations of particle release points that are captured by a well field. To distinguish capture by IWF, AWF and SWF, the dots are color coded dark green, yellow and blue respectively. Two other company well fields, AMPAC and POSSM, also capture particles, as indicated by dots color coded turquoise and pink, respectively. This analysis however, focuses on Tronox well fields. The perchlorate plume boundary is shown on each layer by a red contour, and the chromium plume boundary is shown in pink. Empty areas (i.e., no colored dots) within the perchlorate plume boundary indicate locations from which released particles bypass the three well fields Capture from each layer is discussed below:

1. Figure 6-2 shows the endpoint analysis for Layer 1 particles. Except for small area between the POSSM well field and AWF and some "islands," virtually the entire layer is dry (unsaturated). However, particles from the plume in the small saturated zones are being captured by AWF (yellow) and SWF (blue).
2. Figure 6-3 shows the endpoint analysis for Layer 2 particles. Layer 2 is mostly saturated except for:
    a. an area next to the eastern boundary and outside the plume,
    b. upgradient of the IWF and a few disjointed areas next to the southern boundary and outside the plume.

    Perchlorate from Layer 2 is captured primarily by AWF (yellow particles) and SWF (blue). A narrow area on the north east section of the plume and east of Pabco Road is not captured by any of the extraction fields.
3. Figure 6-4 shows the endpoint analysis for Layer 3 particles. Layer 3 is mostly saturated except for an area adjacent to the eastern boundary of the model domain. For Layers 1 and 2 the perchlorate plume did not extend south of the IWF because these layers are

unsaturated in this area. In Layer 3, the perchlorate plume does extend to the south of IWF, a large part of that portion is captured by the IWF (green). Except for a portion of the plume east of the PabcoRoad, the remaining part of the plume in Layer 3 is captured by AWF (yellow) and SWF (blue).

4. Figure 6-5 shows the endpoint analysis for Layer 4 particles. Layer 4 is fully saturated. The perchlorate plume in Layer 4 is not continuous and is broken into a northern and a southern segment. The south central part, covering most of the Tronox site, terminates at AWF and is virtually fully captured by IWF (dark green), AWF (yellow) and SWF (blue). The northern segment of the plume lies mostly east of Pabco Road. A good portion of the northern segment lying west of Pabco Road is captured by SWF.
5. Figure 6-6 shows the endpoint analysis for Layer 5 particles. Very little of the perchlorate plume extends down to Layer 5. The perchlorate plume in Layer 5 is composed of four disjointed “islands” which represent the tips of the plume bottom. The two southern “islands” on or next to the Tronox property are captured by the IWF (green), AWF (yellow) and the SWF (blue). The northern two “islands” are not captured.
6. Since the perchlorate plume does not extend into Layer 6, no endpoint analysis is needed for this layer.

One of the modeling objectives is to estimate perchlorate travel times and future daylighting of perhclorate from the UMCf to the Qal. Since perchlorate undergoes very little or no retardation, its travel times were calculated based on the time for advective transport along a streamline from bottom of the plume, located in model Layer 5. This is the only layer from which released particles daylight into the Qal beyond the IWF. The travel time from the release point to the Qal/UMCf contact is on the order of 230 years, with an additional 10 years for the same particles to be captured further downgradient at the AWF. The perchlorate daylighting travel times from the bottom of the plume are longer than the orginal time it took to travel down from the source areas (on the order of several decades) for two reasons; first, the total daylighting travel distance is much longer than shorter vertical distance from the source area, and second, strong downward vertical gradients previously existed that accelerated downward migration.

Chromium capture was also evaluated through this endpoint analysis. Chromium is present in groundwater above its 0.1 mg/L RBGC in model layers 2 through 4. As shown on Figures 6-3 through 6-5, the chromium groundwater plume above this concentration generally falls within the 1 mg/L perchlorate plume boundary, demonstrating that the perchlorate capture zones are also effectively capturing chromium. As presented on Figure 6-4 and 6-5, layers 3 and 4 (first two UMCf layers) show some areas of chromium concentration above 0.1 mg/L extending beyond the 1 mg/L perchlorate contour on the eastern fringes of the main Tronox plume.

Although the EVS contours indicate connection with the Tronox plume, this interpretation is based on limited data in these areas, and the data influencing these contours may be associated with potential sources to the east of the Site rather than the Site plume. This will be further evaluated as part of ongoing CZE work.

6.2.7 Three Dimensional Visualization of the Capture Zone

Figure 6-2 through 6-6 along with the discussions above describe capture of the perchlorate plume layer by layer in a two dimensional platform. However, the capture zone is really a three dimensional ("3D") envelope. It is helpful to get a sense of the 3D capture zone. Figures 6-7 and 6-8 were developed in order provide a 3D visualization for the IWF and AWF respectively. To develop these figures Tronox developed two sub-models using Groundwater Vista's® Telescopic Mesh Refinement ("TMR") scheme. Figures 6-7 and 6-8 were developed employing MODAPATH's reverse particle tracking on each of the sub-models. On both the figures reverse particle traces are shown starting from the respective extraction wells. In order to have an uncluttered view only 50 particles were released at each of the extraction wells and their path traced opposite to the direction of travel. The left panels of Figures 6-7 and 6-8 show the extraction wells in short red vertical lines and particle traces in blue changing to aqua marine with increasing distance away from the wells. The left panels of Figures 6-7 and 6-8 also show the equipotential surfaces in green. The particle traces cross the equipotential surfaces orthogonally, however the orthogonality is distorted because of the 10x vertical exaggeration used to facilitate an uncluttered view. The equipotential surfaces and the intersecting particle traces in the lower layers show a vertically upward component as has been understood from numerous monitoring records. The right panels of Figures 6-7 and 6-8 show the same particle traces but instead of the equipotential lines, the contact surface between the Qal and the UMCf is shown.

6.2.8 Capture Efficiencies of the Well Fields

In order to quantitatively evaluate the capture efficiency of the extraction well fields, Tronox developed a mass transport model using the MT3D code (Zheng, 1993). Perchlorate is a conservative tracer that does not suffer any degradation and adsorption. The details of the transport model are presented in Appendix E.

The captured and bypassed perchlorate mass flux for the IWF and the AWF are calculated by defining a thin zone along the plane of the extraction wells and extending the plane to (1) a local boundary and (2) the wider 1 ppm perchlorate plume boundary. At the IWF, the width of the local boundary is defined to extend to the Tronox property line on the eastern side and to the 1 ppm plume on the western side. At the AWF, the local boundary is defined as the width of the capture zone obtained from the endpoint analysis. A narrow zone of grid blocks along that plane is defined for the purpose of perchlorate mass budget. The fraction of mass of perchlorate crossing the plane and captured by the well fields per day is defined as the capture efficiency. Examples of the mass budget zones for Layer 3 at the IWF and the AWF are shown on Figure 6-9. The total mass fluxes and the perchlorate mass budget captured by the field as a fraction of the mass crossing the plane is presented on Table 6-1 below. The increase in the capture efficiency using the local boundary versus the wider 1 ppm plume boundary is around 1% in both well fields, indicating that the contribution of the plume further away from the well fields to the bypassed mass flux is minimal.

Table 6-2

Capture Efficiency of Well Fields

Region	Extent for Estimating Mass Flux	Mass Flux (lbs/day)		% Captured
		Captured	Bypassed	
Interceptor Well Field	1 ppm boundary	353	11	97
Interceptor Well Field	Local boundary	353	8	98
Athens Road Well Field	1 ppm boundary	423	75	85
Athens Road Well Field	Local boundary	423	67	86
Seep Well Field	Not calculated	40	Not calculated	--
All well fields (IWF, AWF, Seep)		816		
Mass flux entering Las Vegas Wash	--	14	--	--

In summary, this evaluation indicates that the IWF attains a capture efficiency of 97 % and the AWF attains a capture efficiency of 85 %. In addition, the SWF captures 40 lbs per day, while 14 lbs/day bypasses the SWF and discharges at the Wash.

The captured mass fluxes using this method were compared with mass removal rates reported for the extraction systems (Northgate, 2010e). The model underestimates the flux at the IWF (353 lbs/day versus a range of 744 – 1001 lbs/day between June 2008 and June 2010), while for the AWF the modeled flux is close to the lower range of measured rates (423 lbs/day versus a range of 571-758 lbs/day). The modeled mass flux at the SWF is in general agreement with the measured fluxes (40 lbs/day versus a range of 32 to 59 lbs/day). The primary reason for this discrepancy at the IWF appears to be related to the interpolation method used for three-dimensional plume model developed in EVS. The plume model likely is underestimating the perchlorate concentrations in the areas close to the IWF and AWF extraction systems. Plume concentrations were calculated by EVS using measured well concentrations assigned to the screened interval mid-point, with the result that concentrations were not considered for some wells that are significantly de-watered. Adjustments to the plume modeling method may be made in the future to improve the interpolation near the well fields, however, the current interpretation is adequate for relative capture evaluation. The current analysis likely underestimates perchlorate concentrations within the area captured, and thus provides a conservative assessment of percent mass flux captured. The actual percentages captured are likely higher than what is presented in the table above.

7 CONCENTRATION TREND EVALUATION

Step 5 of the CZE guidance (USEPA, 2008) recommends evaluating contaminant concentration trends over time in two types of wells:

1. Sentinel wells, located downgradient of the Target Capture Zone and not currently impacted above background concentrations. If capture is successful, contaminant concentrations in these wells should remain at background levels over time.
2. Downgradient performance monitoring wells, located downgradient of the Target Capture Zone and currently impacted above background concentrations. If capture is successful, contaminant concentrations should decline over time, eventually reaching cleanup levels (or background).

As measurable concentrations of both perchlorate and hexavalent chromium appear to extend to the Las Vegas Wash, no available downgradient wells can be defined as sentinel wells (assuming that background concentrations are non-detect). Therefore, the focus of this evaluation was perchlorate and hexavalent chromium concentration trends over time for a number of wells selected as downgradient performance monitoring wells for each well field. Previous concentration trend evaluations performed, and their relevance to this CZE, include:

- Annual Remedial Performance Reports for Chromium and Perchlorate (e.g., Northgate, 2010h): Graphs of perchlorate concentration over time are presented and discussed for the wells in each of the three extraction well fields, as well as for several monitoring well transects between the AWF and SWF (i.e., the Athens Road Piezometer [ARP] transect wells, the City of Henderson Water Reclamation Facility [COH WRF] transect wells, and the Lower Ponds wells). The extraction well concentration trends are not appropriate for CZE; however, the monitoring well transects between the AWF and SWF are all appropriate as downgradient performance monitoring wells for the AWF, and these graphs are therefore included in the evaluation. For hexavalent chromium, the wells evaluated for concentration over time include those in the IWF and AWF well field areas, which are not appropriate for CZE, and the five wells specified for monitoring in the Appendix J of the 1986 Consent Order for removal of chromium from groundwater. Three of these five wells are upgradient of the IWF and are therefore not appropriate for CZE. The well M-72 is located in the “dead zone” between the barrier wall and the downgradient infiltration trenches and concentration trends in this well will be discussed in the future barrier wall evaluation memorandum. Therefore, only well M-86 which is downgradient of the IWF and barrier wall is included in this evaluation.

- Interim Capture Zone Evaluation (Northgate, 2010c): In addition to referencing the concentration over time graphs from the annual remedial performance report, this evaluation included three selected downgradient performance monitoring wells at increasing distances downgradient of the IWF (i.e., wells M-100, M-23 and M-96). These wells are included in this evaluation, along with additional wells (M-101, M-102, M-87, M-88, M-99 and PC-54) selected as IWF downgradient performance monitoring wells.

Table 7-1 and Figure 3-3 indicate the wells selected as downgradient performance monitoring wells. Figure 7-1 through 7-7 present concentration-time plots for the selected wells using all the available chemical data for perchlorate and total chromium. If a primary and duplicate sample were collected during a sampling event, the higher of the two results is used in the plots. Non-detect results are plotted using the laboratory sample quantitation limits. Outliers and anomalous data were screened out based upon professional judgment and studying historical concentration trends, and the specific data points removed are identified in a footnote for each affected plot. Several of the wells used in the evaluation are replacements for earlier monitoring wells that were destroyed or rendered unusable due to burial, damage, or construction activity. In these cases, results from both the original and replacement wells are used in the plots to provide the most complete data set.

7.1 Concentration Trends Downgradient of the Interceptor Well Field

Concentration trends at downgradient monitoring wells M-100, M-101, M-102, M-23, M-86, M-87, M-88, M-96, M-99 and PC-54 (see Figure 3-3) were evaluated to assess capture at the IWF (Figures 7-1 through 7-3).

Wells M-86, M-87 and M-88 are located just downgradient of the infiltration trenches at the Interceptor well field. As shown on Figure 7-1, M-86 and M-87 both exhibited a sharp decline in perchlorate and chromium concentrations following installation of the barrier wall in October 2001and introduction of clean Lake Mead water into the infiltration trenches beginning in 1998. Total chromium and/or perchlorate concentrations in both wells rebounded beginning in late-2005 and have been steady in recent years, though remaining well below the previous highs. This rebound may be attributed to a reduction of infiltration water due to fouling of the recharge trenches with a concomitant dispersal of “dead zone” groundwater (perchlorate and chromium-impacted water trapped between the barrier wall and infiltration trenches) and/or recharge of contaminated water from the underlying Muddy Creek formation. However, perchlorate and chromium concentrations appear to be holding steady since the refurbishment of the trenches in July 2009. Concentrations of total chromium in well M-88 have historically been low and remain steady at less than 1 mg/l. Perchlorate concentrations in M-88 climbed between 1998 and 2001 when the barrier wall was installed, and have remained in the range of 40 to 60 mg/l since 2001. M-86 was inactive from mid-2007 through 2010 during refurbishment of the infiltration trenches, and all three wells were recently plugged and abandoned due to conflicts with soil remediation and excavation activities. Following completion of soil remediation activities, replacement wells will be installed along the transect monitored by these wells at locations approved by NDEP. Extraction wells are currently operating downgradient of the barrier wall to remove and treat "dead zone" groundwater and these replacement wells will be monitored in the future to observe the effect of the removal of "dead zone" groundwater on downgradient contaminant concentrations..

Wells M-99, M-100, M-101 and M-102 are located approximately 1000 feet north of the IWF. As shown on Figure 7-2, all of these wells have shown declining perchlorate and chromium concentrations over time, though perchlorate trends in M-99 have exhibited an inconsistent trend with a broad concentration spike between 2003 and 2006 and a recent increase back to similar levels. M-99 is located downgradient of the western edge of the barrier wall. Concentrations of both perchlorate and chromium in M-102 spiked sharply upwards between 2002 and 2003 as a slug of perchlorate and chromium-impacted groundwater moved through the well, possibly due to changing flow paths brought about by the installation of the barrier wall, then sharply declined. Concentration trends in M-100 and M-101, downgradient of the center of the barrier wall, were relatively steady from 1999 through 2001 then declined sharply beginning in 2001 and now appear asymptotic though they do not approach zero in either well. The residual baseline concentrations in these wells may be due to dispersion of "dead zone" groundwater and/or upward migration of contaminants from the underlying Muddy Creek formation. There are no data for either M-101 or M-102 after mid-2006 and mid-2007, respectively, due to a lowering of the water table and insufficient water for sampling. Overall, the concentration plots indicate that the barrier wall has been effective in significantly reducing downgradient perchlorate and chromium concentrations, although the perchlorate concentrations measured in well M-99 suggest that some perchlorate flowing past the western edge of the wall may be impacting this well. Tronox has been aware that some perchlorate from a high-concentration plume bypasses the Interceptor well field and barrier wall through along the western edge, and has installed additional extraction wells (I-AA and I-AB) to improve capture in this area. These wells are currently being plumbed and connected to the groundwater treatment system, the impact of the additional wells on capture at the IWF has been modeled (Section 8), and will be further evaluated in a future CZE report.

Wells M-23, M-96 and PC-54 are located further downgradient of the IWF near Warm Springs Road (Figure 3-3). As shown in Figure 7-3, these wells have also shown consistent declining perchlorate and chromium concentration trends over time, beginning around 2001 in M-23 and 2003/2004 in M-96 and PC-54. PC-54, located downgradient of well M-102, shows a similar pattern of concentration trends. Although concentrations in these wells do not currently appear to be approaching background (non-detect), concentration trends appear to be flattening and recent concentrations may be due to recharge from the underlying Muddy Creek formation.

7.2 Concentration Trends Downgradient of the Athens Road Well Field

Concentration trends at the Athens Road piezometer wells (ARP-1, ARP-2, ARP-3, ARP-4A, ARP-5A, ARP-6B ARP-7, and MW-K4), the COH WRF wells (MW-K5, PC-53, PC-98R and PC-103) and the Lower Pond wells (PC-56, PC-58, PC-59, PC-60, PC-62 and PC-68) were evaluated to assess capture at the AWF (Figures 7-4 through 7-6). The AWF began full-time operation in October 2002. ART-9 replaced ART-6A as an extraction well in the eastern subchannel in late 2006.

The Athens Road piezometer well line is located approximately 250 feet north of the AWF. No data have been available from wells ARP-2 and -3 since June 2008 because these wells were buried during City of Henderson construction activities. Replacement wells ARP-2A and ARP-3A were installed during the second quarter of 2010 and will be sampled on a quarterly basis starting August 2010. In December 2007, ARP-4A, -5A and -6B replaced ARP-4, -5 and -6A respectively, which were plugged and abandoned to make way for COH area development and drainage ditch construction.

As shown in Figure 7-4, perchlorate concentrations on the western side of the well line in wells ARP-1, -2, and -3 declined rapidly at the start of operation of the AWF, and have remained very low despite a small uptick in recent perchlorate results at ARP-1. In the center of the well line, perchlorate concentrations in ARP-4A have steadily declined since about 2002, and perchlorate and chromium concentrations in ARP-5A declined rapidly after the installation of extraction well ART-9 in 2006 and have remained low. Concentrations in well MW-K4, east of ARP-3A, initially declined with the operation of the AWF and dropped further when ART-9 began pumping, but both chromium and perchlorate concentrations have been trending upwards since mid-2008. On the eastern side of the well line, ARP-6 and -7 also initially declined rapidly, but perchlorate and chromium concentration trends have since been erratic at ARP-6B (recently trending upwards) and perchlorate concentrations, although low, have been trending upwards since 2004 in ARP-7. Overall, the plots indicate that the AWF has been successful at capturing the perchlorate and chromium plumes on the west and central portions of the plume. However, concentration trends at ARP-6B and ARP-7 that, although low, are increasing suggest that some portion of the plume may be evading capture in the eastern subchannel. Increasing trends in well

MW-K4, along with monitoring results from additional wells installed for the CZE in the area, suggest that impacted groundwater may be passing between extraction well pair ART-4/4A and the Muddy Creek high and evading capture.

Intermediate between the Athens Road area and the Seep area are the COH WRF and the Lower Ponds monitor well lines. The COH WRF wells, MW-K5 and PC-53, -98R, and -103 are shown on Figure 7-5. Chromium concentrations in all four wells have been below the laboratory sample quantitation reporting limit for the monitoring period. The two wells in the center of the plume with the highest initial perchlorate concentrations, MW-K5 and PC-98R, have exhibited strong downward trends since the AWF came online, although concentrations in PC-98R have lately stabilized around 20 ppm with occasional sharp downward spikes. Concentrations are erratic but low (less than 5 mg/l) in PC-53, on the east side of the well line. Perchlorate concentrations in well PC-103 to the west have been increasing since early 2005. The reason for the increasing perchlorate concentration trend, which does not reflect trends in the upgradient western ARP wells, is not clear. Water levels in PC-103 have historically averaged several feet higher than adjacent well PC-98R to the east, and groundwater flow in this area may have an easterly component. However, water level interpretation is complicated by a lack of nearby monitoring points west of PC-103 and intermittent infiltration from City of Henderson Water Reclamation Facility ponds. Tronox will continue to monitor concentration trends in PC-103 and evaluate impacts from planned improvements to the AWF in the next CZE.

The Lower Ponds well line is 2,200 feet north of the COH well line. As shown in Figure 7-6, with the exception of well PC-58, perchlorate concentrations declined sharply between 1999 and 2004,and have remained steady or continued a slow decline since about February 2004. Concentrations in well PC-58 have been erratic, generally fluctuating in the range of 4 to 12 mg/l, and remain at levels similar to or slightly lower than those measured in 1999.

7.3 Concentration Trends Downgradient of the Seep Well Field

Concentration trends at downgradient wells PC-96 and PC-97 were evaluated to assess capture at the SWF. As shown in Figure 7-7, perchlorate concentrations in the Seep wells initially declined between 2001 and 2004 to concentrations approaching zero, following the operation of groundwater extraction wells at the SWF. Recently, concentrations have increased slightly since 2008, possibly due to fluctuations in pumping rates in well PC-121 and changes in infiltration patterns from COH WRF ponds.

8 CAPTURE ZONE EVALUATION RESULTS SUMMARY

8.1 Evaluation of Capture with Current Operation

Table 8-1 below summarizes the findings for the various evaluations conducted for this CZE following US EPA guidance (US EPA, 2008). In summary, sufficient data have been collected to develop an adequate conceptual model for CZE at the Site (Step 1 of guidance). Based on previous NDEP input, 95% mass flux capture has been used to define interim target capture for the IWF and AWF (Step 2). The water level interpretations (Step 3), ancillary calculations (part of Step 4), and concentration trends over time (Step 5) corroborate the flow model findings (Step 4), and indicate that the flow model is an effective and accurate tool for evaluating current and predicting future groundwater capture.

As discussed in Section 4, the 1 mg/L perchlorate contour was used to define the plumes because 99% of the groundwater mass at the Site falls within that contour, and even at 1 mg/L there is commingling with other sources to the west and east of the Site. The mass flux evaluation using the model indicates that the capture goal of “95% mass flux” is currently being met at the IWF. At the AWF, at least 86% of the mass flux is calculated to be currently captured, and there is an area west of the UMCf high where capture can and will be improved to achieve 95% (see Section 8.2 below). As discussed in Section 7, capture at the AWF may have been better in this specific area prior to 2008.

Although no specific goal has been set for SWF capture, this evaluation indicates the SWF is significantly capturing the perchlorate mass that migrates past the AWF, and that the flux potentially associated with the Tronox facility represents less than a third of the total 65 lbs/day flux to the Las Vegas Wash measured at the Northshore Road monitoring station. The mass flux analysis (Section 6) indicates that the combined AWF and SWF systems remove between 94% and 97% of the total perchlorate flux calculated at the AWF transect.

Table 8-1
Lines of Evidence for Groundwater Capture

Method	**Results – Current Operation**
Interceptor Well Field	
Water Level Interpretation using KT3D	Indicates horizontal capture zone very similar to that indicated by the flow model.
Particle Tracking with Groundwater Flow Model	Mass flux calculation indicates that 97% of perchlorate is captured based on the entire plume, including that portion to the east of the Site boundary, and that 98% of perchlorate flux is being captured based on the eastern Site boundary. Plume mass calculations also indicate that significantly more than 95% of the perchlorate plume upgradient of the IWF is within the capture envelope. Greater than 95% of chromium is also captured.
Flow Rate and Capture Width Calculations	Calculations indicate the combined pumping rate at the IWF is sufficient to capture the width of the full 1 mg/L plume..
Downgradient Concentration Trends	Overall concentration trends support the flow model capture results. However, well M-99 trend suggests some incomplete capture of higher concentration groundwater at west end of IWF. Trends in wells near barrier wall are complicated by varying trench recharge rates and high concentration groundwater trapped in "dead zone".
Athens Road Well Field	
Water Level Interpretation using KT3D	Indicates horizontal capture zone very similar to that indicated by the flow model (i.e., small area not captured within and west of UMCf high). Narrower capture zone for the eastern channel than indicated by the flow model is the result of the data set used (i.e.,used Tronox data only, while the flow model used regional data for improved definition of the potentiometric surface to the east).
Particle Tracking with Groundwater Flow Model	Mass flux calculation indicates at least 86% of perchlorate is captured at the well field. Actual capture is likely higher because the flow model shows slightly more saturated alluvium than is actually present and plume model may underestimate plume concentrations in drawdown areas.
Flow Rate and Capture Width Calculations	Calculations indicate that the combined pumping rate at the AWF may not be sufficient to capture the width of the local boundary plume under higher hydraulic conductivity conditions.
Downgradient Concentration Trends	Overall concentration trends support flow model capture results. Recent concentration increase in well MW-K4 is consistent with area of non-capture shown by flow model and water level interpretation.
Seep Well Field	
Particle Tracking with Groundwater Flow Model	Mass flux calculation indicates nearly complete capture of Tronox plume mass passing through SWF area.

Downgradient Concentration Trends	Overall concentration trends support flow model capture results.

8.2 Capture Enhancements

As described in Section 1, planned enhancements discussed in the CZE Work Plan (Northgate, 2010c) included the addition of seven new extraction wells at the IWF and deepening well ART-7B at the AWF. Because of the potential breach in capture identified by the flow model immediately to the west of and within the UMCf high at the AWF, the following additional enhancements were identified: 1) increase pumping from ART-3 to the extent possible; 2) switch pumping back from ART-4A to ART-4, because ART-4 appears to be a more efficient and effective well; 3) plumb new well PC-150 as an extraction well and pump to maximum capacity; and, 4) if the interpretation of water levels measured after implementation of these improvements indicate that it is needed to exceed 95% mass flux capture, plumb new UMCf high well PC-149 into system and pump to maximum capacity.

To evaluate the effects of these improvements, Tronox used the calibrated flow model and particle tracking endpoint analysis to simulate flow under these new conditions. Results are presented on Figures 8-1 and 8-2. As discussed above, at least 95% of the perchlorate and chromium flux is already being captured by the IWF and the new wells are not necessary to meet the capture goal. As shown on Figures 8-1 and 8-2, the new wells will enhance the already effective capture provided by the IWF system and barrier wall by improving capture at the east end of the barrier wall (new wells I-AC and I-AD). As shown on Figures 8-1 and 8-2 the improvements discussed above for the AWF would greatly reduce the gap in current capture and based on mass flux calculations would increase capture to at least 95%.

In conclusion, capture goals are met at IWF. Even though the 95% capture goal is being met, recovery enhancement will continue by plumbing in seven new IWF wells. The work is underway and these wells will be pumping by early 2011. At the AWF, pumping from ART-3 has recently been increased to the extent possible and ART-4A pumping has been replaced by pumping from ART-4. Plumbing well PC-150 into the extraction system is currently underway. The effects of these improvements at the AWF will be evaluated one month after PC-150 start-up by measuring water levels and evaluating capture using the KT3D software method described in Section 5. If these improvements are not sufficient to achieve the 95% mass flux goal, well PC-149 will be added to the extraction system.

8.3 Ongoing Capture Zone Evaluations

Capture zone evaluation is an ongoing process, and the following specific CZE activities are planned for the Tronox site:

- Complete refinements to the 3-D plume model to achieve better agreement between the modeled mass flux capture and the well field operational records for mass removal (as discussed in Section 6), so that the mass flux evaluation can be completed and the 3-D plume models validated for potential future use. The expected completion date for this activity is December 2010.
- Evaluate the actual capture improvement achieved by the enhancements described in Section 8.2 through water level measurements and interpretation. This evaluation will be used both to assess percent mass capture at the AWF (see Section 8.2) and to further validate the ability of the flow model to accurately predict the effects of system changes. The expected completion date for this activity is first quarter 2011, and the results of this evaluation will be included in the Annual Remedial Performance Report to be submitted in August.
- Establish with NDEP approval target capture zones that are clear and easy to evaluate for use in future CZE. Target capture zones based on percent perchlorate mass and/or mass flux are subject to significant uncertainty and latitude in interpretation, can be cumbersome to calculate, and may change continuously over time with changing plume conditions. Therefore, Northgate recommends that alternative capture targets be developed in the future that are spatially based or are based on groundwater flow rather than being based on mass or mass flux. These would be interim targets for use in future CZEs conducted until final groundwater remedial objectives are established.
- Conduct routine CZE on a periodic basis. These CZEs will be conducted based on the latest U.S. EPA guidance and the results will be included in annual remedial performance reports.
- Conduct additional CZE as needed for any planned or unplanned changes to groundwater flow (e.g., new or modified groundwater extraction or re-injection systems at neighboring sites, future soil flushing at the Tronox site).

9 REFERENCES

Davis, J.A., Kent, D.B., Coston, J.A., Hess, K.M., and Joye, J.L., 2000. *Multispecies Reactive Tracer Test in an Aquifer with Spacially Variable Chemical Condition: Experimental Design and Observed Tracer Movement,* Water Resources Research, v. 36, p. 119-134.

DBSA, 2008. *Groundwater Flow Model Calibration: BMI Upper and Lower Ponds Area*. Prepared for Basic Remediation Company, Henderson, Nevada, November 2008.

DBSA, 2009. *Summary report for updated groundwater flow model calibration, BMI upper and lower ponds area*, 2009.

ENSR Corporation (ENSR), 2001. *Supplemental Phase II Environmental Conditions Assessment*, April.

ENSR, 2005. *Conceptual Site Model Kerr-McGee Facility, Henderson, Nevada*, Prepared for Kerr-McGee Chemical LLC, Henderson, Nevada, February.

ENSR, 2007a. *Draft Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems,* Tronox, LLC, Henderson, Nevada: ENSR, Camarillo, California, 4020-023-160, May 30.

ENSR, 2007b. *Revised Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems, Tronox LLC, Henderson, Nevada*: ENSR, Camarillo, California, 4020-023-110, August 29.

ENSR, 2008. *Annual Performance Report for Chromium and Perchlorate, July 2007-June 2008, Submitted in Accordance with Chromium Mitigation Program and Perchlorate Performance Consent Orders*: ENSR, Camarillo, California, 4020-023-110, August 28.

Errol Montgomery & Associates, 2000. *Analysis of Rate of Groundwater Movement Based on Results of Tracer and Hydraulic Tests Conducted Between Pittman Lateral and Seep Area.*

Geraghty & Miller, Inc., 1993. *Phase I Environmental Conditions Assessment for The Basic Management, Inc. Industrial Complex, Clark County, Nevada*, April 14.

H+A, 2010. *Work Plan to Conduct an Additional Middle Zone DNAPL Investigation, Henderson, Nevada*, Revision 2.0, May 19.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000,*MODFLOW-2000, the U.S. Geological Survey modular ground-water model User guide to modularization concepts and the Ground-Water Flow Process*: U.S. Geological Survey Open-File Report 00-92, 121 p.

Karanovic, M., Tonkin, M., and Wilson, D. 2009. *KT3D_H2O: A Program for Kriging Water Level Data Using Hydrologic Drift Terms*. Ground Water, Vol. 47, N0. 4:580-586.

Kaufmann, R.F., 1977. *Land and Water Use Impacts on Ground-Water Quality in Las Vegas Valley*, Ground Water, v. 15, no. 1, p. 81-89

Kleinfelder, 1993. *Environmental Conditions Assessment, Kerr-McGee Chemical Corporation, Henderson, Nevada*, April.

LAW Engineering, 1993. *Final Report of Phase I Environmental Conditions Assessment, Volume 1: Text, Titanium Metals Corporation (TIMET), Henderson, Nevada*, April 15.

Leckie, J.O., Appleton, A.R., Ball, N.B., Hayes, K.F., and Honeyman, B.D., 1984. *Adsorptive Removal of Trace Elements from Fly-Ash Pond Effluents onto Iron Oxyhydroxide:* Electric Power Research Institute Report, EPRI-RP-910-1, Palo Alto, California.

McDonald, M. G. and Arlen W. Harbaugh, 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*: USGS Geological Survey Open-File Report , Reston, Virginia.

McGinley, 2007. *Athens Road Well Field Modeling Report – Near BMI Industrial Complex, Henderson, Nevada*: McGinley and Associates, Reno, Nevada, June 30.

Nevada Division of Environmental Protection (NDEP), 2007a. *Comments on the Tronox Semi-Annual Performance Report for Chromium and Perchlorate, dated February 26, 2007*: Las Vegas, Nevada, March 29.

NDEP, 2007b. *Response to NDEP Comments on the Tronox Semi-Annual Performance Report Dated February 28, 2007 and the Required Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems, Henderson, Nevada, Dated May 30, 2007*: Las Vegas, Nevada, June 26.

NDEP, 2007c. *Response to NDEP Comments on the Revised Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems, Tronox LLC, Henderson, Nevada, dated August 29, 2007*: Las Vegas, Nevada, October 3.

NDEP, 2007d. *Response to NDEP Comments on the Revised Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems, Tronox LLC, Henderson, Nevada, dated November 28, 2007*: Las Vegas, Nevada, December 11.

NDEP, 2008. *Response to Annual Remedial Performance Report for Chromium and Perchlorate, dated August 25 2008*: Las Vegas, Nevada, October 6.

NDEP, 2009. BMI Plant Sites and Common Areas Project, Henderson, Nevada*: Hydrogeologic and Lithologic Nomenclature Unification*, January 6.

NDEP, 2010a. *Comments on the Interim Groundwater Capture Evaluation and Vertical Delineation Report*, dated December 23, 2009: Las Vegas, Nevada, January 26.

NDEP, 2010b. Meeting Minutes - WebEx Meeting to Discuss NDEP's April 1, 2010 comments to TRX's March 25, 2010 *Capture Zone Evaluation Work Plan,* April 16.

NDEP, 2010c. *Comments on the Interim Groundwater Capture Evaluation and Vertical Delineation Report*, dated March 23, 2010: Las Vegas, Nevada, April 30.

NDEP, 2010d. *NDEP Response to TRX Letter regarding Seep Access Issues with BMI, dated February 12, 2010*: Las Vegas, Nevada, June 28.

Northgate Environmental Management, Inc. (Northgate), 2007. *Revised Work Plan to Evaluate Effective Groundwater Capture at Tronox Extraction Systems, Tronox LLC, Henderson, Nevada*: Oakland, California, August 27.

Northgate, 2009, *Annual Remedial Performance Report for Chromium and Perchlorate, Tronox LLC, Henderson, Nevada*: Oakland, California, August 21.

Northgate, 2010a. *Health Risk Assessment Work Plan, Tronox LLC Facility, Henderson, Nevada*: Oakland, California, March 9.

Northgate, 2010b, *Response to NDEP's January 26, 2010 Comments Regarding Interim Groundwater Capture Evaluation and Vertical Delineation Report* , dated December 23, 2009: Oakland, California, March 23.

Northgate, 2010c, *Interim Groundwater Capture Evaluation and Vertical Delineation Report, Tronox LLC, Henderson, Nevada*: Oakland, California, March 23.

Northgate, 2010d, *Capture Zone Evaluation Work Plan, Tronox LLC, Henderson, Nevada*: Oakland, California, May 13.

Northgate, 2010e, *Revised Hydrogeologic Modeling Work Plan, Tronox LLC, Henderson, Nevada*: Oakland, California, June 7.

Northgate, 2010f, *Responses to May 26, 2010, NDEP Comments on the Capture Zone Evaluation Work Plan*, dated May 13, 2010: Oakland, California, July 7.

Northgate, 2010g, *Revised Human Health Risk Assessment for Remediation Zone A, Tronox LLC, Henderson, Nevada*: Oakland, California, July 23.

Northgate, 2010h, *Annual Remedial Performance Report for Chromium and Perchlorate, Tronox LLC, Henderson, Nevada*: Oakland, California, August 27.

Northgate, 2010i. *Revised Technical Memorandum: Calculation of Leaching-Based Site-Specific Levels for the Soil-to-Groundwater Pathway Using NDEP Guidance, Tronox LLC, Henderson, Nevada:* Oakland, California, September 9.

Northgate, 2010j. *Technical Memorandum: Hydrogeologic Groundwater Model Inputs, Tronox LLC, Henderson, Nevada:* Oakland, California, October 29.

Northgate, 2010k. *Revised Technical Memorandum: Calculation of Leaching-Based, Site-Specific Levels (LSSLs) for the Soil-to-Groundwater Pathway Using NDEP Guidance, Tronox LLC, Henderson, Nevada:* Oakland, California, November 18.

Northgate, 2010l. *Site-Wide Soil Gas Human Health Risk Assessment, Tronox LLC, Henderson, Nevada*: Oakland, California, November 22.

Pollock, D.W., 1994. *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model*: U.S. Geological Survey Open-File Report 94-464, 6 ch.

Post, V., Kooi, H., & Simmons, C.T., 2007. *Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses,* Ground Water, 45(6), 664-671.

TRONOX, 2007. *Response to Nevada Division of Environmental Protection (NDEP) Comments to the Revised Work Plan to Evaluate Effective Groundwater Capture at Tronox LLC, Henderson, Nevada*: Henderson, Nevada, November 28.

University of Nevada at Las Vegas (UNLV), 2003. *Final Report, The Fate and Transport of Perchlorate in a Contaminated Site in the Las Vegas Valley*, Prepared for USEPA, March.

USEPA, 1989. *Risk Assessment Guidance for Superfund: Volume I—Human Health Evaluation Manual (Part A),* Interim Final: United States Environmental Protection Agency, Office of Emergency and Remedial Response, Washington, DC, EPA/540/1-89/002, December.

USEPA 2002. *Elements for Effective Management of Operating Pump and Treat Systems*, EPA 542-R-02-009: United States Environmental Protection Agency, Washington, D.C., December.

USEPA, 2005. *Capture Zone Analysis for Pump-and-Treat Systems,* EPA NARPM Conference: United States Environmental Protection Agency, Washington, D.C., May 24.

USEPA, 2008. *A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems*: U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/003.

van Geen, A.. Robertson, A.P., and Leckie, J.O., 1994. *Complexation of Carbonate Species at the Goethite Surface: Implications for Adsorption of Metal Ions in Natural Waters, Geochimica et Cosmochimica Acta*, v. 58, p. 2073-2086.

Zachara, J.M., Girvin, D.C., Schmidt, R.L., and Resch, C.T., 1987. *Chromate Adsorption on Amorphous Iron Oxyhydroxides in the Presence of Major Groundwater Ions, Environmental Science and Technology*, v. 21, p. 589-594.

Zheng, C. 1990. *MT3D: A modular three dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in ground-water systems*, U.S. Environmental Protection Agency and R.S. Kerr Environmental Research Laboratory, Ada, Oklahoma.

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